



Towards the standardization of sequence stratigraphy

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ABSTRACT

Sequence stratigraphy emphasizes facies relationships and stratal architecture within a chronological framework. Despite its wide use, sequence stratigraphy has yet to be included in any stratigraphic code or guide. This lack of standardization reflects the existence of competing approaches (or models) and confusing or even conflicting terminology. Standardization of sequence stratigraphy requires the definition of the fundamental model-independent concepts, units, bounding surfaces and workflow that outline the foundation of the method. A standardized scheme needs to be sufficiently broad to encompass all possible choices of approach, rather than being limited to a single approach or model.

A sequence stratigraphic framework includes genetic units that result from the interplay of accommodation and sedimentation (i.e., forced regressive, lowstand and highstand normal regressive, and transgressive), which are bounded by 'sequence stratigraphic' surfaces. Each genetic unit is defined by specific stratal stacking patterns and bounding surfaces, and consists of a tract of correlatable depositional systems (i.e., a 'systems tract'). The mappability of systems tracts and sequence stratigraphic surfaces depends on depositional setting and the types of data available for analysis. It is this high degree of variability in the precise expression of sequence stratigraphic units and bounding surfaces that requires the adoption of a methodology that is sufficiently flexible that it can accommodate the range of likely expressions. The

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integration of outcrop, core, well-log and seismic data affords the optimal approach to the application of sequence stratigraphy. Missing insights from one set of data or another may limit the 'resolution' of the sequence stratigraphic interpretation.

A standardized workflow of sequence stratigraphic analysis requires the identification of all genetic units and bounding surfaces that can be delineated objectively, at the selected scale of observation, within a stratigraphic section. Construction of this model-independent framework of genetic units and bounding surfaces ensures the success of the sequence stratigraphic method. Beyond this, the interpreter may make model-dependent choices with respect to which set of sequence stratigraphic surfaces should be elevated in importance and be selected as sequence boundaries. In practice, the succession often dictates which set of surfaces are best expressed and hold the greatest utility at defining sequence boundaries and quasi-chronostratigraphic units. The nomenclature of systems tracts and sequence stratigraphic surfaces is also model-dependent to some extent, but a standard set of terms is recommended to facilitate communication between all practitioners.

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Contents

1.	Introduction: background and rationale	2
2.	Data sets and objectivity of data	5
2.1.	Data integration	5
2.2.	Limitations of seismic data	6
2.3.	Limitations of outcrop, core, and well-log data	7
2.4.	Objectivity of data and inherent interpretations	8
3.	Model-independent platform of sequence stratigraphy	9
3.1.	Methodology	9
3.2.	Base level and accommodation	10
3.3.	Reference curve of base-level changes	11
3.4.	Events of the base-level cycle	12
3.5.	Genetic types of deposit: normal regressive, forced regressive, transgressive	14
4.	Model-dependent aspects of sequence stratigraphy	15
4.1.	Depositional sequences	17
4.2.	Genetic stratigraphic sequences	17
4.3.	Transgressive–regressive sequences	18
5.	Recommendations	18
5.1.	Standard workflow	18
5.2.	Definition of sequence stratigraphy	19
5.3.	Definition of a 'sequence'	19
5.4.	Parasequences	19
5.5.	Genetic types of deposit: systems tracts	19
5.6.	Sequence stratigraphic surfaces	20
5.7.	Concept of hierarchy	21
6.	Discussion: variability of the sequence stratigraphic model	22
6.1.	Nonmarine settings	22
6.2.	Coastal to shallow-water siliciclastic settings	24
6.3.	Deep-water settings	26
6.4.	Carbonate settings	26
7.	Conclusions	29
	Acknowledgements	29
	References	29

1. Introduction: background and rationale

Sequence stratigraphy is considered by many as one of the latest conceptual revolutions in the broad field of sedimentary geology (Miall, 1995), revamping the methodology of stratigraphic analysis. Applications of sequence stratigraphy cover a tremendous range, from deciphering the Earth's geological record of local to global changes in paleogeography and the controls governing sedimentary processes, to improving the success of petroleum exploration and production. Multiple data sets are integrated for this purpose, and insights from several disciplines are required (Fig. 1).

Sequence stratigraphy is uniquely focused on analyzing changes in facies and geometric character of strata and identification of key surfaces to determine the chronological order of basin filling and erosional events. Stratal stacking patterns respond to the interplay of changes

in rates of sedimentation and base level, and reflect combinations of depositional trends that include progradation, retrogradation, aggradation and downcutting. Each stratal stacking pattern defines a particular genetic type of deposit (i.e., 'transgressive', 'normal regressive' and 'forced regressive'; Hunt and Tucker, 1992; Posamentier and Morris, 2000; Fig. 2), with a distinct geometry and facies preservation style. These deposits are *generic* from an environmental perspective (i.e., they can be identified in different depositional settings), and may include tracts of several age-equivalent depositional systems (i.e., systems tracts).

Sequence stratigraphy can be an effective tool for correlation on both local and regional scales. The method is now commonly utilized as the modern approach to integrated stratigraphic analysis, combining insights from all other types of stratigraphic as well as several non-stratigraphic disciplines (Fig. 1). However, it remains the only

- **Academia:** genesis, evolution and internal architecture of sedimentary-basin fills
- **Government:** mapping and correlation on a regional to basin scale
- **Industry:** exploration and production - petroleum plays, coal, mineral resources

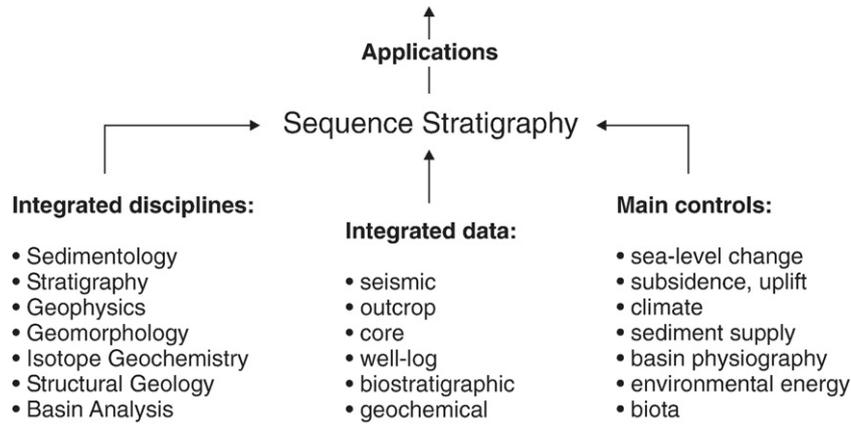


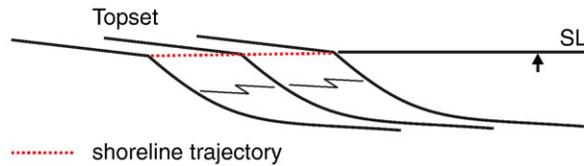
Fig. 1. Sequence stratigraphy in the context of interdisciplinary research.

stratigraphic method that has no standardized stratigraphic code. Efforts have been made by both the North American Commission on Stratigraphic Nomenclature (NACSN) and the International Subcommittee on Stratigraphic Classification (ISSC) with respect to standardizing the method of sequence stratigraphy in the North American Stratigraphic Code (herein referred to as the Code) and the International Stratigraphic Guide (herein referred to as the Guide) respectively. The ISSC Working Group on Sequence Stratigraphy submitted its final report in 1999, without reaching a consensus regarding sequence stratigraphic nomenclature and methodology. At the same time, the long-standing

NACSN committee on allostratigraphy and sequence stratigraphy tabled its efforts in 2002, concluding that it was premature to recognize formal sequence stratigraphic units in the Code.

The process of standardization is hampered mainly because consensus needs to be reached between ‘schools’ that promote rather different approaches (or models) with respect to how the sequence stratigraphic method should be applied to the rock record (Figs. 3 and 4). The need for standardization, however, is evident from the present state of procedural and nomenclatural confusion within sequence stratigraphy (Figs. 3 and 4). Despite numerous debates that have promoted one model over others,

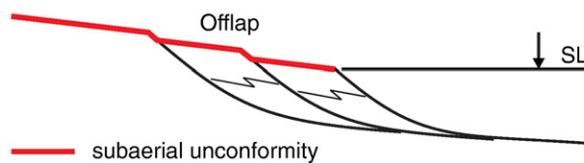
Normal regression



Definition: progradation driven by sediment supply. Sedimentation rates outpace the rates of base-level rise at the coastline.

Depositional trend: progradation with aggradation.

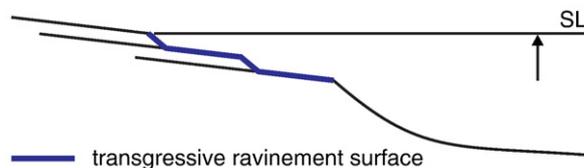
Forced regression



Definition: progradation driven by base-level fall. The coastline is forced to regress, irrespective of sediment supply.

Depositional trend: progradation with downstepping.

Transgression



Definition: retrogradation (backstepping) driven by base-level rise. The rates of base-level rise outpace the sedimentation rates at the coastline.

Depositional trend: retrogradation.

Fig. 2. Genetic types of deposits: normal regressive, forced regressive, transgressive. Zigzag lines indicate lateral changes of facies within the same sedimentary bodies (e.g., individual prograding lobes). The diagram shows the possible types of shoreline trajectory during changes (rise or fall) in base level. During a stillstand of base level (not shown), the shoreline may undergo sediment-driven progradation (normal regression, where the topset is replaced by toplap), erosional transgression, or no movement at all. However, due to the complexity of independent variables that interplay to control base-level changes, it is unlikely to maintain stillstand conditions for any extended period of time.

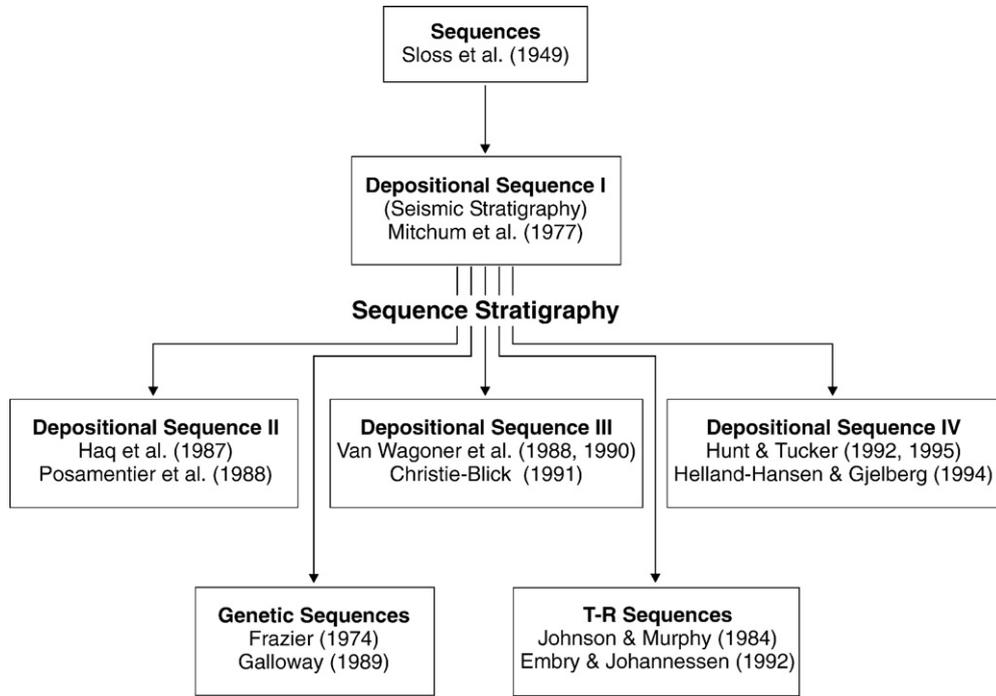


Fig. 3. Sequence stratigraphic models (from Catuneanu, 2006; modified after Donovan, 2001).

there has been no general acceptance of any single approach to sequence stratigraphic analysis. Here, we do not intend to reopen the debate about the relative merits of different approaches. Instead, we examine the points of agreement and difference between existing models, evaluate the reasons for this diversity of opinion, and conclude by identifying common

ground. We then use this common ground as the basis for the definition of a process-based workflow that transcends the boundaries between individual models.

After over 30 years of sequence stratigraphic research and developments, it is fair to conclude that each model is justifiable in

Sequence model Events	Depositional Sequence II	Depositional Sequence III	Depositional Sequence IV	Genetic Sequence	T-R Sequence
end of transgression	HST	early HST	HST	HST	RST
				MFS	
end of regression	TST	TST	TST	TST	TST
					MRS
end of base-level fall	late LST (wedge)	LST	LST	late LST (wedge)	
			CC**		
onset of base-level fall	early LST (fan)	late HST	FSST	early LST (fan)	RST
	CC*				
	HST	early HST	HST	HST	

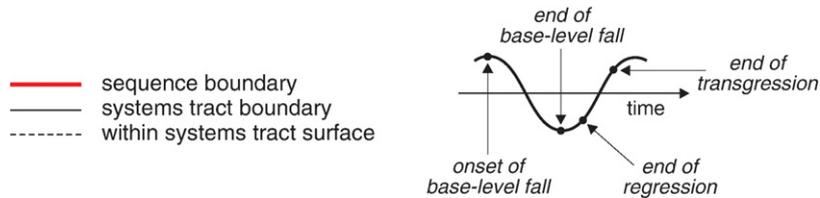


Fig. 4. Nomenclature of systems tracts and timing of sequence boundaries for the existing sequence stratigraphic models (from Catuneanu, 2006). Abbreviations: LST – lowstand systems tract; TST – transgressive systems tract; HST – highstand systems tract; FSST – falling-stage systems tract; RST – regressive systems tract; T-R – transgressive–regressive; CC* – correlative conformity *sensu* Posamentier and Allen (1999); CC** – correlative conformity *sensu* Hunt and Tucker (1992); MFS – maximum flooding surface; MRS – maximum regressive surface. References for the proponents of the various sequence models are provided in Fig. 3.

Key: $\sqrt{\sqrt{\sqrt{\quad}}}$ good
 $\sqrt{\sqrt{\quad}}$ fair
 $\sqrt{\quad}$ poor

	Rock data			Geophysical data		
	Outcrops		Core	Well logs	Seismic data	
	Large-scale	Small-scale			2D	3D
Tectonic setting	$\sqrt{\sqrt{\quad}}$	$\sqrt{\quad}$	$\sqrt{\quad}$	$\sqrt{\sqrt{\quad}}$	$\sqrt{\sqrt{\sqrt{\quad}}}$	$\sqrt{\sqrt{\sqrt{\quad}}}$
Facies	$\sqrt{\sqrt{\sqrt{\quad}}}$	$\sqrt{\sqrt{\sqrt{\quad}}}$	$\sqrt{\sqrt{\sqrt{\quad}}}$	$\sqrt{\sqrt{\quad}}$	$\sqrt{\quad}$	$\sqrt{\sqrt{\quad}}$
Nature of contacts	$\sqrt{\sqrt{\sqrt{\quad}}}$	$\sqrt{\sqrt{\sqrt{\quad}}}$	$\sqrt{\sqrt{\sqrt{\quad}}}$	$\sqrt{\sqrt{\quad}}$	$\sqrt{\sqrt{\quad}}$	$\sqrt{\sqrt{\quad}}$
Stratal terminations	$\sqrt{\sqrt{\sqrt{\quad}}}$	$\sqrt{\quad}$	$\sqrt{\quad}$	$\sqrt{\quad}$	$\sqrt{\sqrt{\sqrt{\quad}}}$	$\sqrt{\sqrt{\sqrt{\quad}}}$
Depositional trends	$\sqrt{\sqrt{\sqrt{\quad}}}$	$\sqrt{\sqrt{\quad}}$	$\sqrt{\sqrt{\quad}}$	$\sqrt{\sqrt{\quad}}$	$\sqrt{\sqrt{\quad}}$	$\sqrt{\sqrt{\sqrt{\quad}}}$
Stratal geometries	$\sqrt{\sqrt{\quad}}$	$\sqrt{\quad}$	$\sqrt{\quad}$	$\sqrt{\quad}$	$\sqrt{\sqrt{\sqrt{\quad}}}$	$\sqrt{\sqrt{\sqrt{\quad}}}$
Depositional elements	$\sqrt{\sqrt{\sqrt{\quad}}}$	$\sqrt{\sqrt{\quad}}$	$\sqrt{\sqrt{\quad}}$	$\sqrt{\sqrt{\quad}}$	$\sqrt{\quad}$	$\sqrt{\sqrt{\sqrt{\quad}}}$
Depositional systems	$\sqrt{\sqrt{\sqrt{\quad}}}$	$\sqrt{\sqrt{\quad}}$	$\sqrt{\sqrt{\quad}}$	$\sqrt{\sqrt{\quad}}$	$\sqrt{\quad}$	$\sqrt{\sqrt{\sqrt{\quad}}}$

Fig. 5. Utility of different data sets for building a sequence stratigraphic framework (from Catuneanu, 2006). The seismic and large-scale outcrop data provide continuous subsurface and surface information respectively. In contrast, small-scale outcrops, core, and well logs provide sparse data collected from discrete locations within the basin.

the context in which it was proposed and may provide the optimum approach under the right circumstances. One reason for the co-existence of contrasting approaches is that each sequence stratigraphic ‘school’ is validated by the working experience of its proponents on the basis of different case studies or data sets that support their methodology. Consequently, the best approach to undertaking a sequence-stratigraphic analysis of a succession (i.e., which model is ‘best’) may vary with the tectonic setting, depositional setting, sediment types (siliciclastics, carbonates, evaporites), the data set available for analysis (e.g., seismic data versus well logs or outcrop observations), and even the scale of observation.

This paper aims to provide guidelines for a standard workflow of sequence stratigraphic analysis. For this purpose, it is necessary to define and separate the model-independent from the model-dependent aspects of sequence stratigraphy. The approach proposed herein recognizes that, beyond a standard workflow, flexibility needs to be retained for applying sequence stratigraphy on a case-by-case basis. For example, depending on the depositional system and the types of data available, each model-dependent set of sequence-bounding surfaces may be present or absent, mappable or cryptic, thus forcing the selection of an optimum model for the final conceptual packaging of the strata under study into sequences. Finding the right balance

between a model-independent workflow, which can be standardized, and flexibility is at the forefront of what a revised Code or Guide needs to provide to the geological community.

2. Data sets and objectivity of data

2.1. Data integration

The sequence stratigraphic method yields optimum results when information derived from multiple data sets, including seismic, outcrop, core, well log, biostratigraphic and geochemical, are integrated (Fig. 1). Not all these types of data may be available in every case study, a factor which may limit the ‘resolution’ of the sequence stratigraphic model. For example, onshore ‘mature’ petroleum basins may offer the entire range of data sets, whereas offshore ‘frontier’ basins may initially be interpreted in stratigraphic terms only through the analysis of seismic data. Working models are refined as more data become available, as, for example, when well logs and cores are added to the subsurface seismic data base following the initial seismic stratigraphic survey.

Integration of data is important because each data set contributes different insights regarding the recognition of depositional trends and stratal stacking patterns (Figs. 5 and 6). Notably, seismic data provide

Data set	Main applications /contributions to sequence stratigraphic analysis
Seismic data	Continuous subsurface imaging; structural styles; lapout relationships; stratal stacking patterns; imaging of depositional elements; geomorphology; stratal geometries.
Well-log data	Vertical stacking patterns; grading trends; depositional elements; depositional systems; petrophysics; calibration of seismic data.
Core data	Facies; textures and sedimentary structures; nature of stratigraphic contacts; physical rock properties; paleocurrents in oriented core; calibration of well-log and seismic data.
Outcrop data	3-D control on facies architecture; insights into process sedimentology; facies; depositional elements; depositional systems; all other applications afforded by core data.

Fig. 6. Contributions of different data sets to the sequence stratigraphic interpretation (from Catuneanu, 2006). Integration of insights afforded by various data sets is the key to a reliable and complete sequence stratigraphic model.

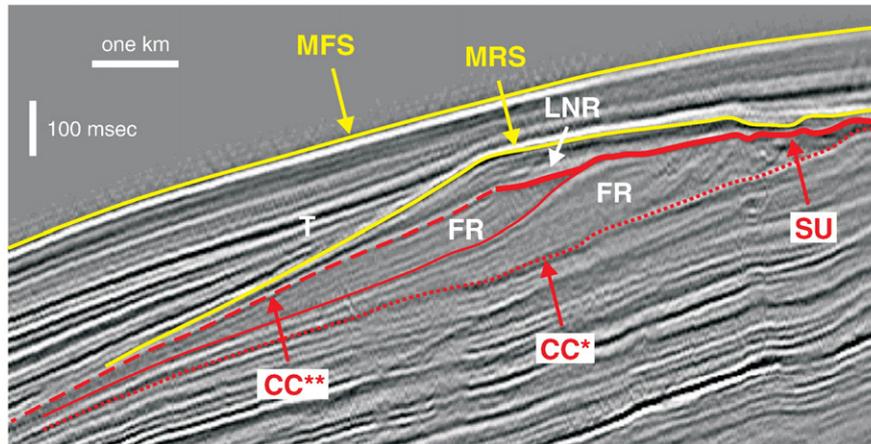


Fig. 7. Seismic line in the Gulf of Mexico showing different genetic types of deposits (forced regressive, normal regressive, transgressive) and stratigraphic surfaces that may serve as sequence boundaries according to different sequence stratigraphic models (modified from Posamentier and Kolla, 2003). Abbreviations: FR – forced regressive; LNR – lowstand normal regressive; T – transgressive; SU – subaerial unconformity; CC* – correlative conformity *sensu* Posamentier and Allen, 1999 (=basal surface of forced regression); CC** – correlative conformity *sensu* Hunt and Tucker, 1992; MRS – maximum regressive surface; MFS – maximum flooding surface. The line displays the typical stacking patterns and stratal terminations associated with forced regression (offlap, downlap, toplap, truncation), normal regression (downlap, topset), and transgression (onlap).

continuous coverage of relatively large areas at the expense of vertical resolution, whereas outcrops, core and well logs may provide the opportunity for more detailed studies in particular locations but within the context of a sparse and discontinuous data base. Therefore, the types of data presented in Figs. 5 and 6 complement each other and may be calibrated against each other. Mutual calibration is important because the interpretation of any type of data may involve some subjectivity. The limitations involved in interpreting any types of data need to be understood and acknowledged.

2.2. Limitations of seismic data

A number of fundamental applications of sequence stratigraphy are subject to uncertainty if seismic data are not used, since lapout relationships, best observed on seismic profiles, are a key to the physical recognition of sequence stratigraphic surfaces. Systems tracts were first defined on the basis of stratal stacking patterns interpreted from the architecture and lapout terminations of seismic reflections (Vail et al., 1977; Brown and Fisher, 1977). Traditionally, seismic data have not been used to define stratigraphic units in codes or guides because the establishment of earlier formal guiding documents preceded the availability of such data. Stratigraphic codes and guides need to adapt to the now widespread application of seismic stratigraphy and to recognize the importance of seismic data in sequence stratigraphic analyses.

Seismic data afford the observation of stratal terminations (lap-outs), stratal stacking patterns on 2D profiles, and 3D visualization of stratigraphic surfaces and depositional elements in the subsurface (Posamentier, 2000). However, the information provided by conventional exploration data (i.e., 20–40 Hz) is limited by the vertical seismic resolution, which filters out the ‘details’ (i.e., the higher frequency cycles) that may be present in the subsurface. The ability to resolve cycles that may be amalgamated within one single reflection is improving continuously as techniques of seismic data acquisition and processing progress. The fact that seismic reflection architecture increases in complexity as resolution improves has always been recognized (Cartwright et al., 1993). In the early days of seismic stratigraphy, the vertical seismic resolution was 20–30 m or more, whereas more recent multichannel seismic data have 5 m of vertical resolution or less, depending on the depth of investigation. Features such as lateral-accretion surfaces within fluvial point bars, scroll bars, or tidal channels can now be seen on 2D lines, horizon slices or 3D visualization maps. The latest 3D visualization techniques allow us to

take virtual tours through seismic volumes, to ‘walk’ along interpreted unconformities. Conventional seismic stratigraphy has given way to the more sedimentological insights of seismic geomorphology, which allows examination of channels or other depositional or erosional elements, or analysis of the type of sediment gravity-flow deposits that fill submarine canyons and other deep-water channelized or lobate systems. Despite this innovation in technology and science of stratigraphic imaging, seismic stratigraphic concepts have yet to be incorporated into stratigraphic codes or guides.

Vertical seismic resolution limits the scale of observation and may constrain what can be deduced from any particular case study. In regional petroleum exploration, where the focus is on mapping higher

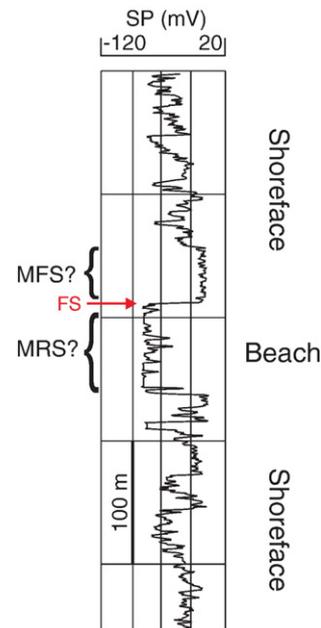


Fig. 8. Spontaneous potential (SP) log from a dominantly shallow-water succession in the Gulf of Mexico. The log illustrates the uncertainty that can affect the placement of the maximum regressive and maximum flooding surfaces in the case of monotonous lithological successions that lack obvious grading trends. The same problem affects the interpretation of outcrops which expose ‘massive’ beds (no grading). In this example, the uncertainty is in the range of tens of meters. Abbreviations: FS – flooding surface; MRS – maximum regressive surface; MFS – maximum flooding surface.

rank (i.e., larger scale) sequences and systems tracts, vertical seismic resolution is no longer an important limitation. Correlative conformities (Fig. 4) can be mapped on the basis of observable changes in stratal stacking patterns, within the few-meter interval that corresponds to an individual seismic reflection (Fig. 7). Although higher frequency units may be missed because they are amalgamated within a single reflection, sequence stratigraphic surfaces of higher rank can be mapped and used to construct a sequence stratigraphic framework at that particular hierarchical level. The amalgamation of high-frequency cycles within single reflections, as the wavelength of the cycles approaches the resolution limit of the data, is a contributing factor to the dominance of the ‘third-order’ frameworks in many seismic stratigraphic interpretations (Nummedal, 2004). In local reservoir studies where interpretation is commonly required below the vertical seismic resolution, the higher frequency sequence stratigraphic framework may be resolved by using core and/or well logs. Such an increase in stratigraphic resolution is the norm where the focus changes from exploration to production and more data become available as a result of drilling activity.

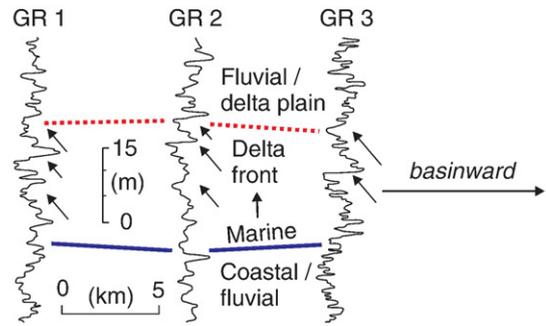
2.3. Limitations of outcrop, core, and well-log data

The interpretation of outcrops, cores and well logs in terms of the position of various sequence stratigraphic surfaces may be affected by uncertainties that rival the vertical resolution of seismic data. For example, pinpointing the surface that is interpreted to mark the time of maximum shoreline transgression along a depositional-dip transect (i.e., a ‘maximum flooding surface’) within a condensed section of meters or tens of meters of shale may involve a margin of error equivalent to the thickness of the condensed section. Similarly, pinpointing the surface that is interpreted to mark the time of maximum shoreline regression along a depositional-dip transect (i.e., a ‘maximum regressive surface’) within thick and massive (‘blocky’ on well logs) shallow-water sandstones is equally challenging and potentially subject to significant uncertainty (Fig. 8).

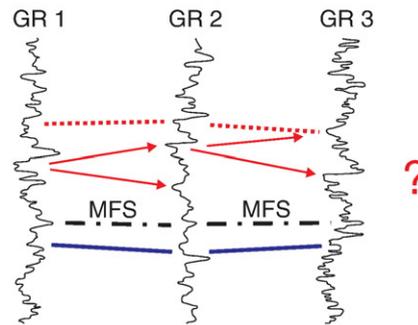
With the exception of monotonous lithological successions that show minimal changes in grain size, outcrops, cores and well logs present the opportunity to observe vertical textural (grading) trends. Such trends can then be used to interpret the position of sequence stratigraphic surfaces whose timing depends on sediment supply. Examples include maximum flooding and maximum regressive surfaces in siliciclastic shallow-water settings, interpreted at the top of fining-upward and coarsening-upward trends respectively. Similar textural trends may be observed on carbonate platforms, where transgressions and regressions modify the shale-to-carbonate ratio, resulting in the accumulation of ‘dirtier’ or ‘cleaner’ limestones respectively. However, this ratio may also be affected by the relative ‘health’ of the carbonate factory (i.e., the production rate of carbonate sediment), which may depend on factors other than terrigenous sediment supply. The exclusive usage of grain size for the identification of maximum flooding and maximum regressive surfaces is, therefore, simplistic, and may involve a significant uncertainty. In a deltaic setting, for example, autocyclic shifting of prograding lobes may cause the top-of-coarsening-upward surface (interpreted as the ‘maximum regressive surface’) to be a diachronous facies contact, with components that are much older than the end of regression. In this case, the ‘maximum regressive surface’ is a composite surface, which consists of multiple individual segments of different ages.

Notwithstanding the potential for error in the interpretation of shallow-water successions, textural trends of fining- or coarsening-upward, in this particular depositional setting, can be used to map those surfaces *the timing of which depends on sediment supply*. As sediment supply may vary significantly along a coastline, such surfaces, which correspond to the end-of-regression and end-of-transgression ‘events’, may be highly diachronous along strike, even within the limits of biostratigraphic resolution (Gill and Cobban, 1973;

A Well-log cross-section



B Options for correlation



C Interpreted cross-section

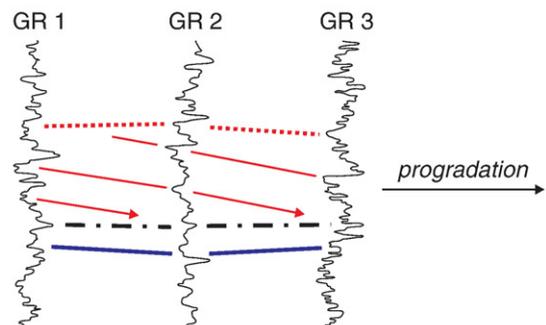


Fig. 9. Workflow in the correlation of well logs in a transitional marine to nonmarine setting (Upper Cretaceous, central Alberta). A. Well-log cross-section: arrows indicate coarsening-upward trends, interpreted as prograding lobes (or ‘parasequences’), on the gamma-ray (GR) logs. The solid line of correlation is a transgressive wave-ravinement surface (base of transgressive marine deposits). The dotted correlation line is a facies contact at the top of delta front facies. B. Options for the correlation of the prograding lobes. The selection of the option that makes most geological sense is based on a *facies model* of deltaic progradation which indicates that clinoforms downlap the maximum flooding surface in a basinward (i.e., easterly) direction (C). The maximum flooding surface (MFS) is interpreted at the top of the fining-upward trends that overlie the transgressive wave-ravinement surface. C. Interpreted cross-section: the steps involved in the interpretation include (1) the identification of prograding lobes on individual well logs (A), and (2) the correlation of these lobes between isolated data control points (well logs in this case) based on the predictions of a facies model of deltaic progradation (C).

Martinsen and Helland-Hansen, 1995; Catuneanu et al., 1998; Posamentier and Allen, 1999; Catuneanu, 2006). In contrast, sequence stratigraphic surfaces that form in relation to changes in the direction of base-level shift at the coastline, and so in essence *independently of sediment supply* (e.g., ‘correlative conformities’ in Fig. 4), are more suitable for building a chronostratigraphic framework. These surfaces

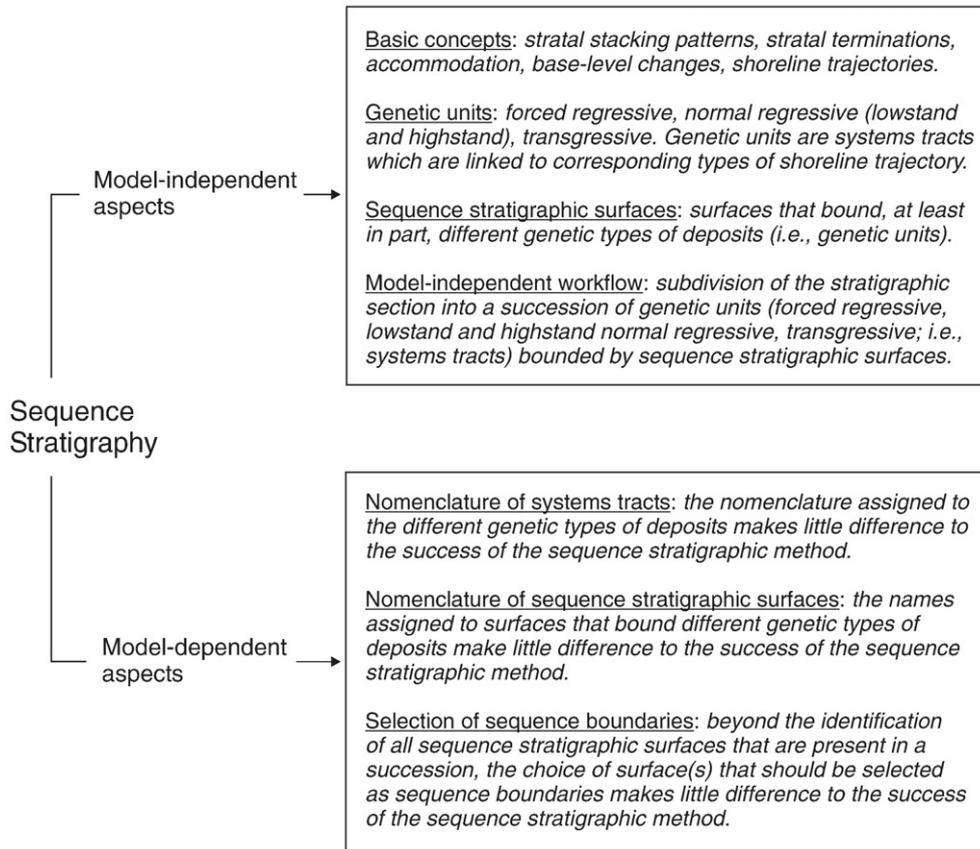


Fig. 10. Model-independent versus model-dependent aspects of sequence stratigraphy. The model-independent aspects form the core platform of the method that is validated by all 'schools'. The model-dependent aspects can be left to the discretion of the practitioner; such flexibility allows one to adapt more easily to the particularities of each case study. Depending on situation, any one of the models may provide the optimum approach to the sequence stratigraphic analysis. For example, the selection of sequence boundaries may depend on depositional setting or the type of data available for analysis.

are potentially synchronous over larger areas than the sediment-supply-controlled surfaces, although neither of them are truly chronostratigraphic (see Catuneanu, 2006, for a comprehensive discussion of the time attributes of stratigraphic surfaces). Because their timing is independent of sediment supply, the criteria employed for mapping 'correlative conformities' are not based on changes from coarsening- to fining-upward or vice versa but rather on changes in stratal stacking patterns that are best observed on seismic lines.

It is also important to note that the two 'correlative conformities' in Figure 4 mark the start and end of forced regression (Fig. 2), and therefore they bracket the period of time when there is minimal or no fluvial accommodation. This means that the sediment delivered to the shoreline is coarser during forced regression than it is during normal regression (Posamentier and Morris, 2000; Catuneanu, 2006). Thus, the correlative conformity at the base of forced regressive deposits may be marked by an increase in average grain size, whereas the correlative conformity at the top of forced regressive deposits may correspond to a decrease in average grain size during continued

progradation (Morris et al., 1995; Posamentier et al., 1995; Posamentier and Morris, 2000; Catuneanu, 2006). Such textural changes may provide criteria to infer the position of the two types of correlative conformities in outcrop and core studies. Additional field criteria for the distinction between 'normal' and 'forced' regressive deposits, and implicitly for the identification of the 'correlative conformities' that separate them, have been provided by Eberli et al., (1994), Spence and Tucker (1997), Posamentier and Morris (2000), Playton and Kerans (2002), MacNeil and Jones (2006), Bover-Arnal et al. (2008), for both carbonate and siliciclastic systems. The distinction between 'normal' and 'forced' regression is important because they are fundamentally different in terms of processes active at the time of sedimentation, as well as in terms of associated petroleum plays (e.g., Posamentier and Morris, 2000; Catuneanu, 2006).

2.4. Objectivity of data and inherent interpretations

All sequence stratigraphic methodologies in Figs. 3 and 4 are based on the study of data, whether seismic, outcrop, core, well-log or any combination thereof. At the same time, interpretations are inherent in the observation and processing of any type of data. In fact, there is an intimate relationship between observations afforded by data and interpretations. A case can be made that there is no such thing as pure 'observation' in geology (Rudwick, 1996; Miall and Miall, 2001). Practically all observations carry with them some form of interpretation, otherwise they lack context and become essentially meaningless. This is true for the observations of any kind of data, from outcrop to seismic.

In the case of a sparse and discontinuous data base, such as one built by isolated outcrops, core or well logs, detailed correlation between

Observations:

- litho-, bio-, chemofacies
- stratigraphic contacts
- stratal terminations
- stratal stacking patterns
- stratal geometries

Interpretations:

- depositional elements
- depositional systems
- sequence stratigraphic surfaces
- systems tracts
- sequences

Fig. 11. Basic observations and interpretations involved in the sequence stratigraphic methodology.

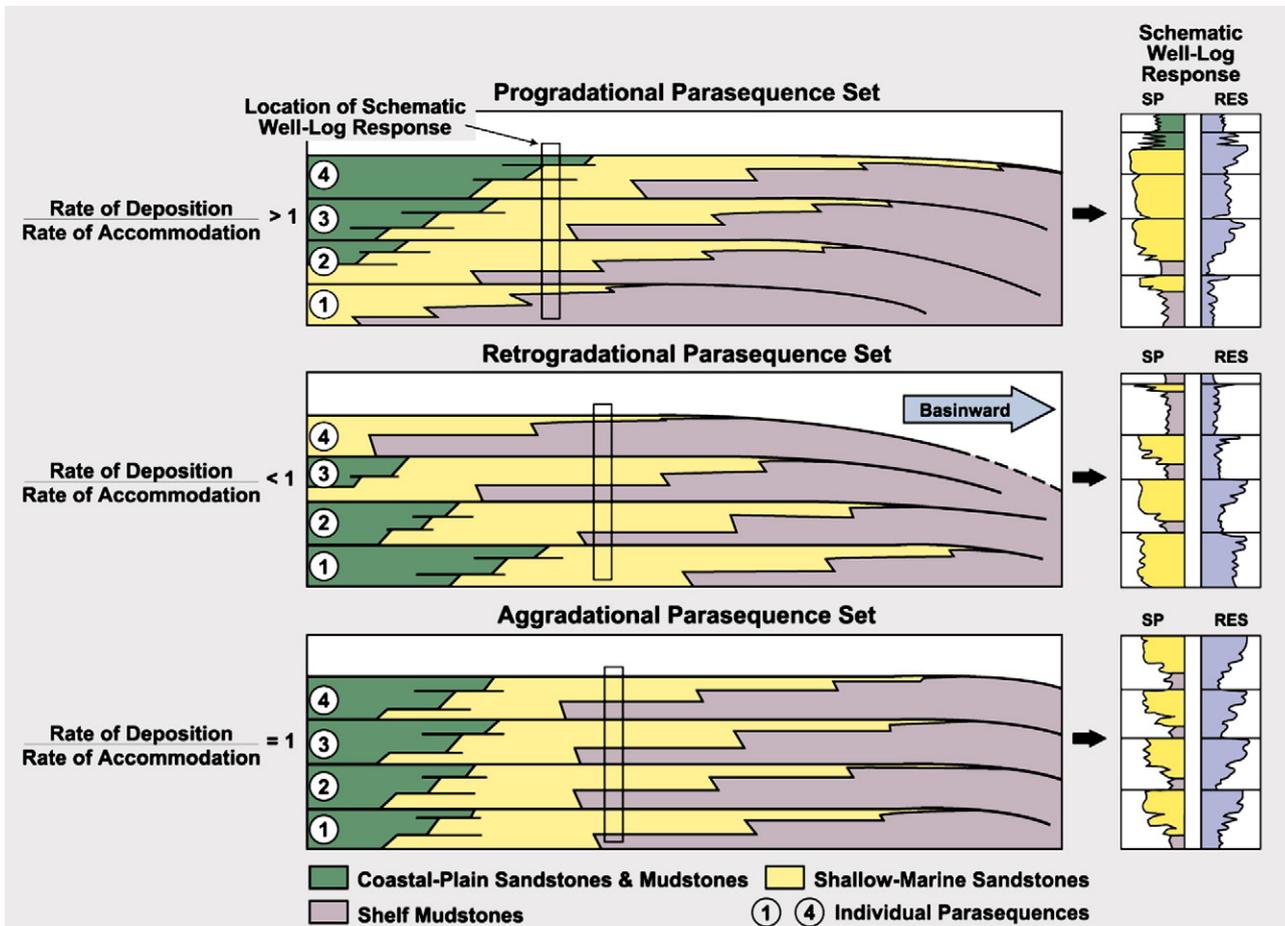


Fig. 12. Vertical stacking of parasequence sets (from Van Wagoner et al., 1990).

discrete control points may rely entirely on facies models. The gaps between data are filled with lines of correlation (interpreted surfaces) that fulfill the prediction of generally accepted models. To that extent, anyone who constructs a stratigraphic cross-section of correlation uses a conceptual model to drive their interpretation. An example is provided in Fig. 9, where well logs are used to correlate prograding lobes along the depositional dip of a deltaic system. The uninterpreted cross-section (Fig. 9A) indicates the presence of two or three parasequences at each location. In the absence of time control, which is commonly the norm at this high-frequency level, the correlation of parasequences may be performed in different ways (Fig. 9B), and the choice of the most realistic interpretation is based entirely on a facies model of deltaic progradation (Fig. 9C). In this case, the clinofolds interpreted in Fig. 9C comply with a *model* which predicts that clinofolds downlap the maximum flooding surface in a basinward direction. The validity of such 'model-driven' interpretations can only be checked by using independent data, as with production figures in the case of subsurface reservoirs.

3. Model-independent platform of sequence stratigraphy

All current sequence stratigraphic approaches include a common set of fundamental principles and concepts. These define a model-independent methodology that can therefore be standardized (Fig. 10). Outside of this common ground, model-dependent choices include nomenclatural preferences, and the selection of surfaces that should be elevated to the rank of sequence boundary (Figs. 4 and 10). The separation between model-independent and model-dependent aspects of sequence stratigraphy provides the key to the inclusion of

sequence stratigraphic units and surfaces in stratigraphic codes and guides, and to the definition of a core workflow for the sequence stratigraphic method.

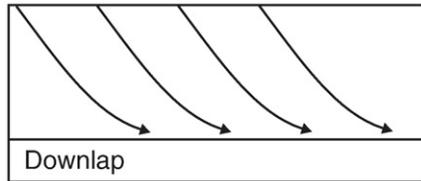
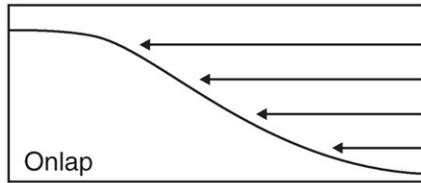
3.1. Methodology

One of the most important and least described aspects of sequence stratigraphy is related to the method. After the 1970's, when Robert Mitchum and his colleagues described the sequence stratigraphic methodology and definitions (e.g., Mitchum, 1977; Mitchum and Vail, 1977; Mitchum et al., 1977; Ramasayer, 1979), most of the scientific papers regarding the evolution of sequence stratigraphic concepts have focused on the models (e.g., Jervey, 1988; Posamentier and Vail, 1988; Hunt and Tucker, 1992; Embry, 1995; Paola, 2000; Plint and Nummedal, 2000; Catuneanu, 2002).

The strength of the sequence stratigraphic methodology is the emphasis on basic observations, which include: the types of facies (litho-, bio-, chemo-); the nature of stratigraphic contacts (conformable, unconformable); the pattern of vertical stacking of facies (depositional trends); the strike variability of facies belts; stratal terminations (lapouts); and stratal geometries (Fig. 11). Each of these basic observations may provide critical information for placement of stratigraphic surfaces and definition of systems tracts. The opportunity to collect all this information may depend on the type of data available and the scale of observation (Figs. 5 and 6).

Vertical stacking of parasequence sets can be classified as progradational, retrogradational and aggradational (Van Wagoner et al., 1990; Fig. 12), and is defined on the basis of observed vertical facies relationships. For example, in a progradational stacking pattern

TERMINATIONS ABOVE A SURFACE



TERMINATIONS BELOW A SURFACE

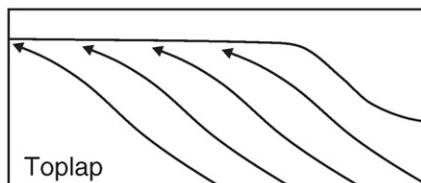
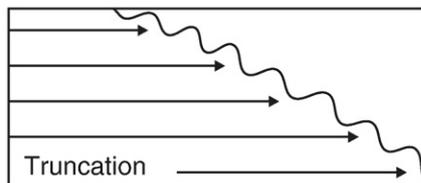


Fig. 13. Stratal terminations that can be observed above or below a stratigraphic surface in seismic profiles and larger scale outcrops (from Mitchum and Vail, 1977).

successively younger strata contain lithologies indicative of more proximal facies than the underlying strata. In addition to the observation of vertical changes in proximal versus distal trends, sedimentological understanding of strike variability of facies belts has also advanced to the level that this now must be considered in building a sequence stratigraphic framework.

Stratal terminations were originally defined by Mitchum et al. (1977) when interpreting reflection seismic profiles, although they can also be observed in large, seismic-scale outcrops (Fig. 13). Four stratal terminations can be used to identify sequence stratigraphic surfaces, two occurring above a surface (onlap and downlap), and two occurring below a surface (truncation and toplap). In addition, offlap is a key stratal stacking pattern that affords the recognition of forced regressions and the delineation of subaerial unconformities and their correlative conformities (Figs. 2 and 7). Such lapouts are useful to the interpretation of depositional trends (Fig. 2), and hence systems tracts.

Stratal geometries, together with stratal terminations, can be used to define surfaces and systems tracts, and also to infer accommodation conditions at the time of deposition. A key geometric element to be observed is the paleo-shelf break and its trajectory in a prograding package. The trajectory of the paleo-shelf break (Steel and Olsen, 2002) is used to interpret changes in accommodation on the shelf (area located updip from the shelf break) (e.g., Johannessen and Steel, 2005; Carvajal and Steel, 2006). A sigmoid prograding package (Mitchum and Vail, 1977) shows a parallelism of the upper stratal segments (topsets) indicating a continuous up-building (aggradation) of the topsets during progradation, and an upstepping shelf-break trajectory (Fig. 14). This

implies creation of shelfal accommodation during progradation. An oblique prograding package (Mitchum and Vail, 1977) shows toplap terminations at the top and downlap terminations at the base, and a more horizontal shelf-break trajectory (Fig. 14). This type of progradation is characterized by the lack of topsets, and indicates little or no accommodation on the shelf during progradation. Similar inferences in terms of available accommodation are also afforded by the observation of changes in the trajectory of the paleo-shoreline within a stratigraphic section (Helland-Hansen and Martinsen, 1996).

Based on such observations, the sequence stratigraphic methodology can be summarized in four steps: (1) observe stacking trends and stratal terminations; (2) use stacking patterns and/or stratal terminal patterns to delineate sequence stratigraphic surfaces; (3) use surfaces, stacking patterns and stratal geometries to identify systems tracts; and (4) use surfaces and systems tracts to define stratigraphic sequences.

3.2. Base level and accommodation

The relationship between stratal stacking patterns and cyclic changes in base level is a fundamental theme of sequence stratigraphy. This relationship was emphasized even before the definition of sequence stratigraphy as a method in the 1970's and the 1980's (e.g., Barrell, 1917; Wheeler and Murray, 1957; Wheeler, 1958, 1959; Sloss, 1962; Wheeler, 1964). The concept of 'base level' delineates a dynamic surface of balance between erosion and deposition. Equivalent definitions place this equilibrium surface at the lowest level of continental erosion, at the lowest point on a fluvial profile, or at the highest level up to which a sedimentary succession can be built (Twenhofel, 1939; Sloss, 1962). The amount of space that is available for sediments to fill up to the base level defines the concept of 'accommodation' (Jervey, 1988). A rise in base level creates accommodation, whereas a fall in base level destroys accommodation. Base level is commonly approximated as sea level (e.g., Jervey, 1988; Schumm, 1993; Posamentier and Allen, 1999), although it can lie below sea level depending on the erosive action of waves and other subaqueous currents. When base level is approximated as sea level, the concept of 'base-level change' becomes equivalent with the concept of 'relative sea-level change' (Posamentier et al., 1988).

The association between base level and sea level does not imply that the applicability of the sequence stratigraphic method is limited to marine deposits. In fact, the methodology applies to all depositional settings. Accommodation in fluvial settings may also be modified by changes in base level, and where rivers are too far inland from base-level influence, fluvial accommodation may still be created or destroyed by climate change or tectonism. To that extent, accommodation is more universal than base level as a control on stratigraphic cyclicity in all depositional settings.

The concept of base level is generally used in the context of marine or lacustrine settings. The equivalent in the alluvial realm is the graded fluvial profile. The marine base level and the downstream portion of the graded fluvial profile often have a process-response relationship in which the graded fluvial profile is anchored by and responds to fluctuations in the marine base level (Posamentier and Allen, 1999; Catuneanu, 2006). It has been suggested that these two concepts can be amalgamated into the concept of 'stratigraphic base level' that marks the surface of equilibrium between sedimentation and erosion in all depositional settings (Cross and Lessenger, 1998). A stratigraphic base level positioned below the topographic or bathymetric profile (landscape or seascape) is referred to as 'negative' accommodation, and may trigger downcutting. A stratigraphic base level above these profiles marks 'positive' accommodation, and may be accompanied by sediment accumulation. In the context of updip fluvial systems which are out of range of sea-level change influence, the upper limit of fluvial accommodation is defined by changes in discharge regimes and sediment supply, as they control equilibrium floodplain height (Blum and Törnqvist, 2000). In turn, discharge

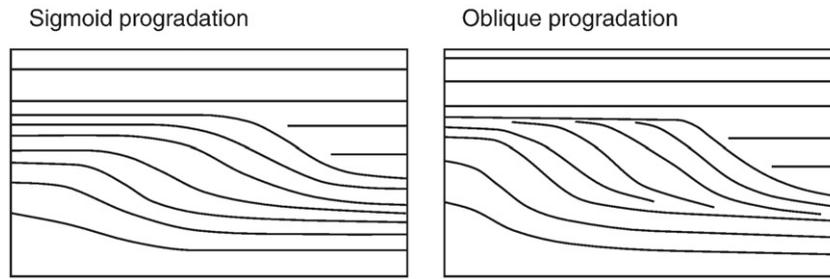


Fig. 14. Stratal geometries associated with a prograding shelf-slope system (from Mitchum and Vail, 1977). A sigmoid geometry indicates positive accommodation on the shelf during progradation. An oblique geometry indicates little or no accommodation on the shelf during progradation.

regimes and sediment supply are modified by ‘upstream controls’ such as climate and tectonism. In such inland settings, changes in the graded fluvial profile are commonly offset temporally relative to changes in the (marine) base level. For this reason, it is preferable to keep the concepts of graded fluvial profile and base level separate, as opposed to combining them into a single ‘stratigraphic base level’ (Blum and Törnqvist, 2000; Catuneanu, 2006).

Base level may fluctuate over a wide range of temporal scales. Short-term shifts in base level, over sub-geologic time scales, depend mainly on changes in the balance between sediment supply and environmental energy flux (Catuneanu, 2006). In areas of high sediment supply, base level may rise to sea level and progradation occurs. During times (or in areas) of higher energy, base level may lie below the sea floor and subaqueous erosion occurs. Base level may in some cases be represented by wave base, which may control the accretion of carbonate sediments in shallow-water settings (Calvet and Tucker, 1988; Osleger, 1991). Fluctuations in energy flux, such as between fairweather and storm conditions, will cause changes in base level at a frequency much greater than those typically attributed to allogenic controls.

Over geologic time scales, base-level changes are controlled primarily by allogenic mechanisms, including tectonism and sea-level change (eustasy). Climate cycles driven by orbital forcing may exert an indirect control on accommodation, by inducing sea-level fluctuations through glacioeustasy and thermal expansion or contraction processes. This indirect control affects sedimentation within marine environments and the downstream portion of fluvial systems that respond to sea-level fluctuations. Beyond the influence of the marine environment, within the upstream reaches of fluvial systems, climate cycles may control fluvial processes of aggradation or erosion

by modifying the balance between fluvial discharge and sediment load. In such settings, climate exerts a direct control on graded profiles and fluvial accommodation.

While the role of fluctuating base level is central to sequence stratigraphy, autocyclic controls may also leave an important imprint on the architecture of the stratigraphic record. At the scale of individual depositional settings, the tendency for self organization toward the most energy-efficient state of equilibrium may generate stratigraphic signatures similar to those produced by allogenic mechanisms. Examples include shifts from shoreline regression to transgression in response to lobe switching and the lateral migration of sediment bodies, without changes in the overall rates of sediment supply or of base-level rise; the generation of stepped surfaces during transgression; and the generation of multiple terrace-pairs and multiple incisions during constant rate of base-level fall (Muto and Steel, 2001a,b, 2004). The discussion below lays emphasis on the allogenic component of mechanisms controlling development of stratigraphic architecture, which provides the template for stratigraphic predictability at the regional scale of a sedimentary basin. Superimposed on this framework of sequence stratigraphic units and bounding surfaces, autogenic processes add another degree of complexity to the rock record, and therefore they should not be overlooked in the interpretation of any particular stratigraphic succession.

3.3. Reference curve of base-level changes

The interpretation of sequence stratigraphic surfaces and systems tracts is not based on inferred correlations with local or global cycle charts, but rather on observations of stratal stacking patterns and

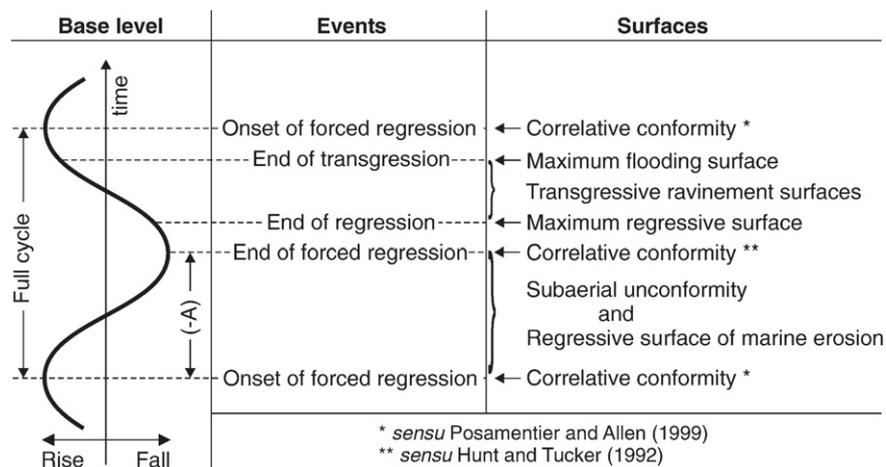


Fig. 15. Timing of the seven surfaces of sequence stratigraphy relative to the four events of the base-level cycle (from Catuneanu, 2006). The reference curve of base-level change reflects fluctuations in base level along the coastline. The timing of the four events is unique along each dip line, but it may change along strike due to variations in sediment supply and/or subsidence rates. Although a symmetrical reference curve is used here (and in Fig. 16) for illustrative purposes, the actual curve may be either symmetrical or asymmetrical, depending on the interplay between the various driving mechanism(s) responsible for the fluctuations in base level. The erosion that generates transgressive ravinement surfaces may be triggered by waves or tides (hence the usage of plural). Abbreviation: (-A) – negative accommodation.

facies relationships from outcrops, cores, well logs, and seismic data (Van Wagoner et al., 1987, 1990; Van Wagoner, 1995; Posamentier and Allen, 1999; Catuneanu, 2006). Once identified on the basis of such data, the relative timing of formation of sequence stratigraphic surfaces and systems tracts can be interpreted in terms of specific events or stages of a base-level cycle (Fig. 15). For example, the onset-of-a-base-level-fall 'event' leads predictably to a change in shoreline trajectory from progradation with aggradation, attributed to base-level rise, to subsequent progradation and downstepping attributed to base-level fall. The latter type of architecture defines 'forced regressive' deposits (Posamentier et al., 1992; Posamentier and Morris, 2000), and the surface that bounds them at the base is identified on the basis of stratal stacking patterns and inferred to correlate in time with the onset-of-base-level-fall 'event'. Similar inferences between the timing of shifts in stratal stacking patterns and the events of a reference curve of base-level changes are made for all sequence stratigraphic surfaces (Fig. 15).

Subsidence rates vary both between and within sedimentary basins, affecting the pattern and the timing of base-level changes from one location to another. As a result, the curves describing fluctuations in base level through time are location-specific, and so are the amounts of accommodation that are made available for sediment accumulation. Therefore, no single curve of base-level change can describe quantitatively the variations in accommodation across a sedimentary basin. Notwithstanding this variability, the fluctuations in base level that are relevant to the formation of systems tracts and the sequence stratigraphic surfaces that separate them are the ones recorded within the *coastal area* of any basin that includes a marine (or lacustrine) setting. This is because the timing of the generation of sequence stratigraphic surfaces is tied to changes in shoreline trajectory that reflect corresponding shifts in depositional trends. For example, a maximum flooding surface forms when the *shoreline* trajectory changes from transgressive (retrogradation) to regressive (progradation). Along dip lines, the coastline is intercepted only once

and hence sequence stratigraphic surfaces are closer to time lines (e.g., there is only one moment in time when the shoreline changes from transgression to regression along a dip-oriented profile). Along strike, however, variations in subsidence rates and sediment supply may affect the timing of the shifts in depositional trends along the coastline (Martinsen and Helland-Hansen, 1995; Catuneanu et al., 1998; Posamentier and Allen, 1999; Catuneanu, 2006). This makes sequence stratigraphic surfaces more diachronous along strike, and particularly those whose timing depends not only on base-level changes (affected by differential subsidence; e.g., the two correlative conformities in Fig. 15) but also on variations in sediment supply (e.g., the maximum regressive and maximum flooding surfaces in Fig. 15). As shown by flume work (Heller et al., 2001), the strike diachroneity of sequence stratigraphic surfaces tends to be more evident during slow changes in base level. This diachroneity may affect the ability to correlate systems tracts at regional scales (Anderson et al., 2004; Anderson, 2005).

3.4. Events of the base-level cycle

Changes in depositional trends at any location along a coastline mark events that are important to the chronology of a sequence stratigraphic framework. Four such events (i.e., levels of highest, lowest, most seaward and most landward position of shoreline; Helland-Hansen and Martinsen, 1996) may be recorded during a full cycle of base-level change, as a result of the interplay between sediment accumulation and available accommodation *at the shoreline* (Figs. 4, 15 and 16). The timing of these events is unique along each dip line, but it may change along strike due to variations in sediment supply and/or subsidence rates as discussed above:

- (1) onset of a forced regression (onset of base-level fall at the shoreline);
- (2) end of a forced regression (end of base-level fall at the shoreline);

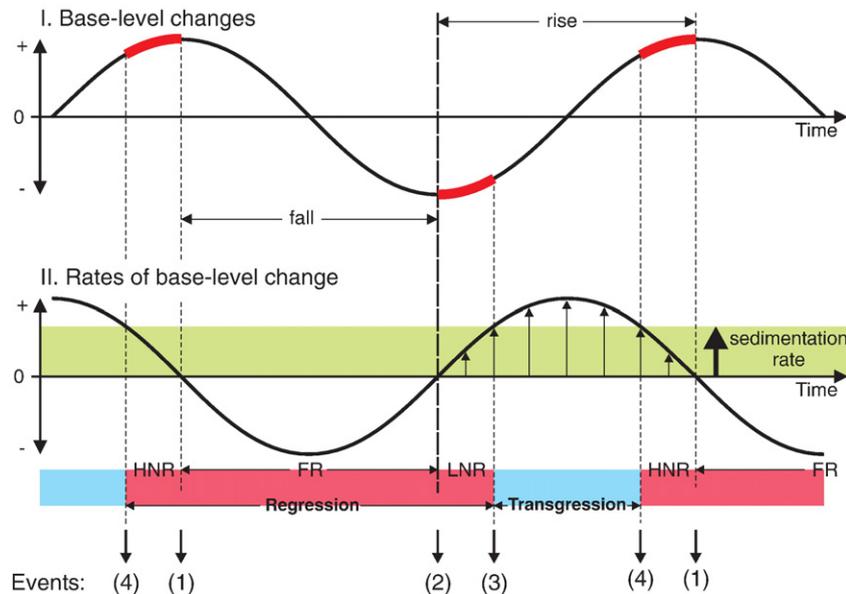


Fig. 16. Concepts of transgression, normal regression, and forced regression, as defined by the interplay of base-level changes and sedimentation at the shoreline (from Catuneanu, 2006). The top sine curve shows the magnitude of base-level changes through time. The thicker portions on this curve indicate early and late stages of base-level rise ('lowstand' and 'highstand' normal regressions respectively), when the rates of base-level rise (increasing from zero and decreasing to zero, respectively) are outpaced by sedimentation rates. The sine curve below shows the rates of base-level changes. Note that the rates of base-level change are zero at the end of base-level rise and base-level fall stages (the change from rise to fall and from fall to rise requires the motion to cease). The rates of base-level change are the highest at the inflection points on the top curve. Transgressions occur when the rates of base-level rise outpace the sedimentation rates. For simplicity, the sedimentation rates are kept constant during the cycle of base-level shifts. The reference base-level curve is shown as a symmetrical sine curve for simplicity, but no inference is made that this should be the case in the geological record. In fact, asymmetrical shapes are more likely (e.g., glacio-eustatic cycles are strongly asymmetrical, as ice melts quicker than it builds up), but this does not change the fundamental principles illustrated in this diagram. Abbreviations: FR – forced regression; LNR – lowstand normal regression; HNR – highstand normal regression. The four events of the base-level cycle are the same as the ones illustrated in Fig. 15: (1) – onset of forced regression; (2) – end of forced regression; (3) – end of regression; (4) – end of transgression.

Events	Sequence stratigraphic surfaces	Depositional setting		
		Nonmarine	Coastal to Shallow-Water	Deep-Water ⁽¹⁾
End of transgression	MFS	Present	Present	Present
	TRS	Absent	Present	Absent
End of regression	MRS	Present	Present	Present
End of FR	CC **	Absent	Present	Present
	RSME	Absent	Present	Absent
	SU	Present	Present ⁽²⁾	Absent
Onset of FR	CC *	Absent	Present	Present

Fig. 17. Sequence stratigraphic surfaces as a function of depositional setting. Each surface that exists in a depositional setting may be mappable or cryptic, depending on the types of data that are available for analysis and the way in which accommodation and sedimentation interacted at the time of formation. Abbreviations: FR – forced regression; CC – correlative conformities; * *sensu* Posamentier and Allen (1999), ** *sensu* Hunt and Tucker (1992); SU – subaerial unconformity; RSME – regressive surface of marine erosion; MRS – maximum regressive surface; TRS – transgressive ravinement surface; MFS – maximum flooding surface; ⁽¹⁾ – submarine fan complex; ⁽²⁾ – if overlain by nonmarine facies.

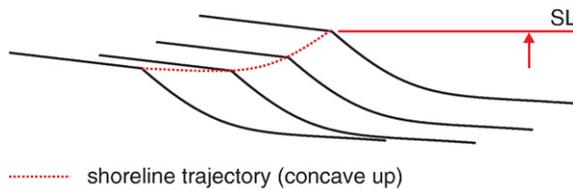
- (3) end of a regression (during base-level rise, when the rate of base-level rise creates accommodation that overwhelms the rate of sedimentation at the shoreline);
- (4) end of a transgression (during base-level rise, when the rate of sedimentation at the shoreline once again exceeds the accommodation created by base-level rise at that location).

Irrespective of the terminology applied to sequence stratigraphic surfaces and the packages of strata between them, the four main events of the base-level cycle mark changes in the type of shoreline trajectory, and implicitly, changes in stratal stacking patterns in the rock record. The *onset-of-forced-regression* event marks a shift from

aggradation to downstepping with continued seaward stepping. The *end-of-forced-regression* event signifies the shift from downstepping to aggradation with continued progradation. The *end-of-regression* event marks the change from progradation to retrogradation. Finally, the *end-of-transgression* event marks the shift in stacking patterns from backstepping/retreat of the shoreline (i.e., retrogradation) to forestepping/advance of the shoreline (i.e., progradation).

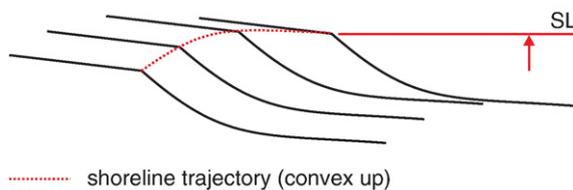
These four events control the timing of formation of all sequence stratigraphic surfaces and systems tracts, and are recognized to varying degrees by all sequence stratigraphic ‘schools’. The expression in the rock record of each one of the four events of the base-level cycle may vary from mappable to cryptic, depending on depositional

Lowstand normal regression (accelerating base-level rise)



The rates of progradation decrease with time, the rates of aggradation increase with time.

Highstand normal regression (decelerating base-level rise)



The rates of progradation increase with time, the rates of aggradation decrease with time.

Fig. 18. Stratal stacking patterns of ‘lowstand’ and ‘highstand’ normal regressions (modified from Catuneanu, 2006). In both cases progradation is driven by sediment supply: sedimentation rates outpace the rates of base-level rise at the shoreline. Lowstand normal regressions record a change in depositional trends from dominantly progradational to dominantly aggradational (concave up shoreline trajectory). In contrast, highstand normal regressions record a change from aggradation to progradation (convex up shoreline trajectory). These depositional trends reflect the pattern of change in the rates of creation of accommodation during the two types of normal regression (Fig. 16). See Fig. 19 for seismic examples.

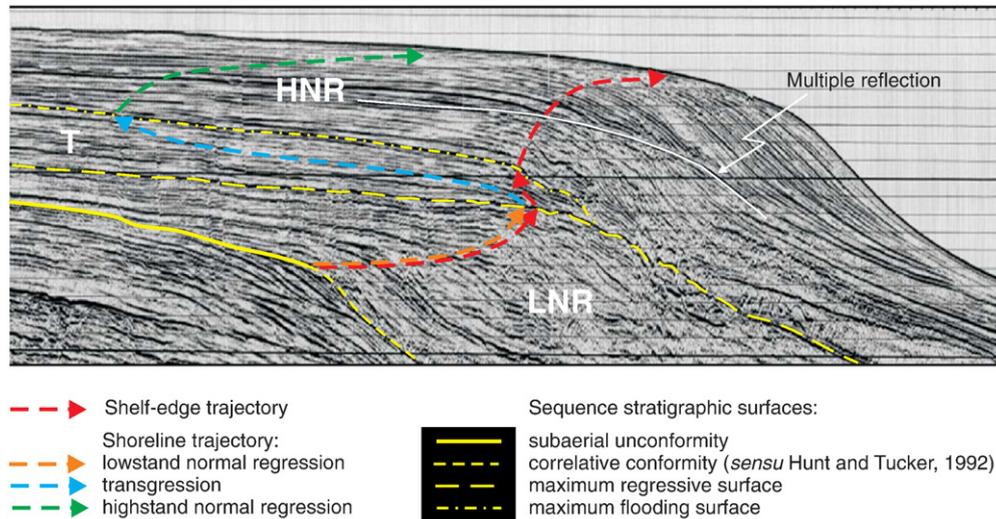


Fig. 19. Dip regional seismic profile from the Pelotas Basin, southern Brazil (modified from Abreu, 1998), showing large-scale (high-rank) lowstand normal regressive (LNR), transgressive (T) and highstand normal regressive (HNR) systems tracts. Lower rank sequences are nested within these higher rank systems tracts. The transgressive systems tract thickens landward, which reflects the direction of shift of the depocenter. Individual backstepping parasequences are difficult to observe within the transgressive systems tract due to the limitation imposed by vertical seismic resolution. Such backstepping parasequences are often easier to observe on well-log cross sections (Fig. 20). The shoreline trajectory and the shelf-edge trajectory may coincide during lowstand normal regression, but are separate during transgression and highstand normal regression. The change in depositional trends from dominantly progradational to dominantly aggradational is typical for lowstand normal regressions (Fig. 18). Conversely, the change in depositional trends from dominantly aggradational to dominantly progradational is typical for highstand normal regressions (Fig. 18). Horizontal scale: approximately 50 km. Vertical scale: 2 seconds two-way travel time.

setting, tectonic setting, and the type(s) of data available for analysis. Beyond the issue of mappability, the specific depositional setting may or may not be conducive to the formation of the sequence stratigraphic surfaces shown in Fig. 15 (Fig. 17).

3.5. Genetic types of deposit: normal regressive, forced regressive, transgressive

In a complete scenario, a full cycle of base-level change includes two stages of sediment-driven 'normal' regression (lowstand and highstand), an intervening stage of shoreline transgression, and a stage of 'forced' regression driven by base-level fall (Fig. 16). Each of these stages results in the formation of a particular genetic type of deposit, with characteristic stratal stacking patterns and sediment distribution within the basin (Figs. 2, 7, 18–21). The terminology applied to these genetic units, which form in relation to particular types of shoreline trajectory (Fig. 2), may vary with the model (Fig. 4). An example of such nomenclatural conflict is offered by the forced

regressive deposits, which may be referred to as 'early lowstand', 'late highstand' or 'falling-stage' systems tract (Fig. 4). The choice of nomenclature is of secondary importance to the recognition that this unit is generated by forced regression. Each genetic type of deposit may include different petroleum plays, so their correct interpretation and separation is more important than their assigned names and position within a sequence.

The succession of stages and events during a full cycle of base-level change in Fig. 16 represents a complete scenario, where sedimentation rates are within the range of the fluctuation of the rates of base-level rise. Incomplete versions of stratigraphic cyclicity may be encountered depending on the case study, where some stages may not be represented in the rock record because favorable conditions have not been met for the formation or preservation of particular genetic units. The completeness of the stratigraphic section in terms of component systems tracts may also be a function of the scale of observation. For example, a consistently high sediment supply that outpaces the amount of space created by base-level rise may prevent the manifestation of long-term

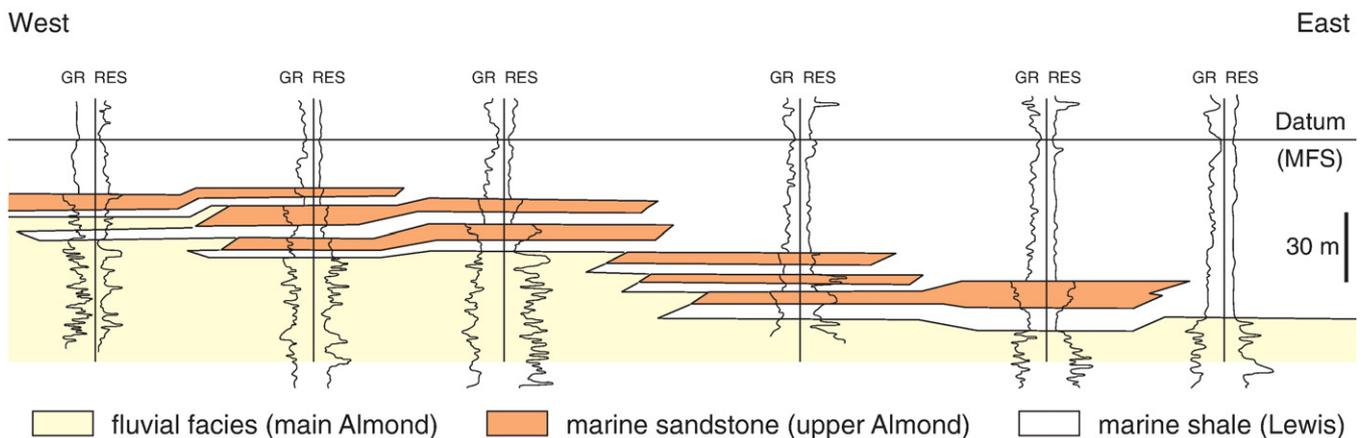


Fig. 20. Regional well-log cross-section of the Almond Formation in the Washakie Basin, Wyoming (modified from Weimer, 1966; Martinsen and Christensen, 1992; and C. Bartberger, pers. comm.) The backstepping stacking pattern of parasequences records the westward transgression of the Western Interior Campanian Seaway. The cross-section is approximately 65 km long. Well logs shown: gamma ray (GR) and resistivity (RES).

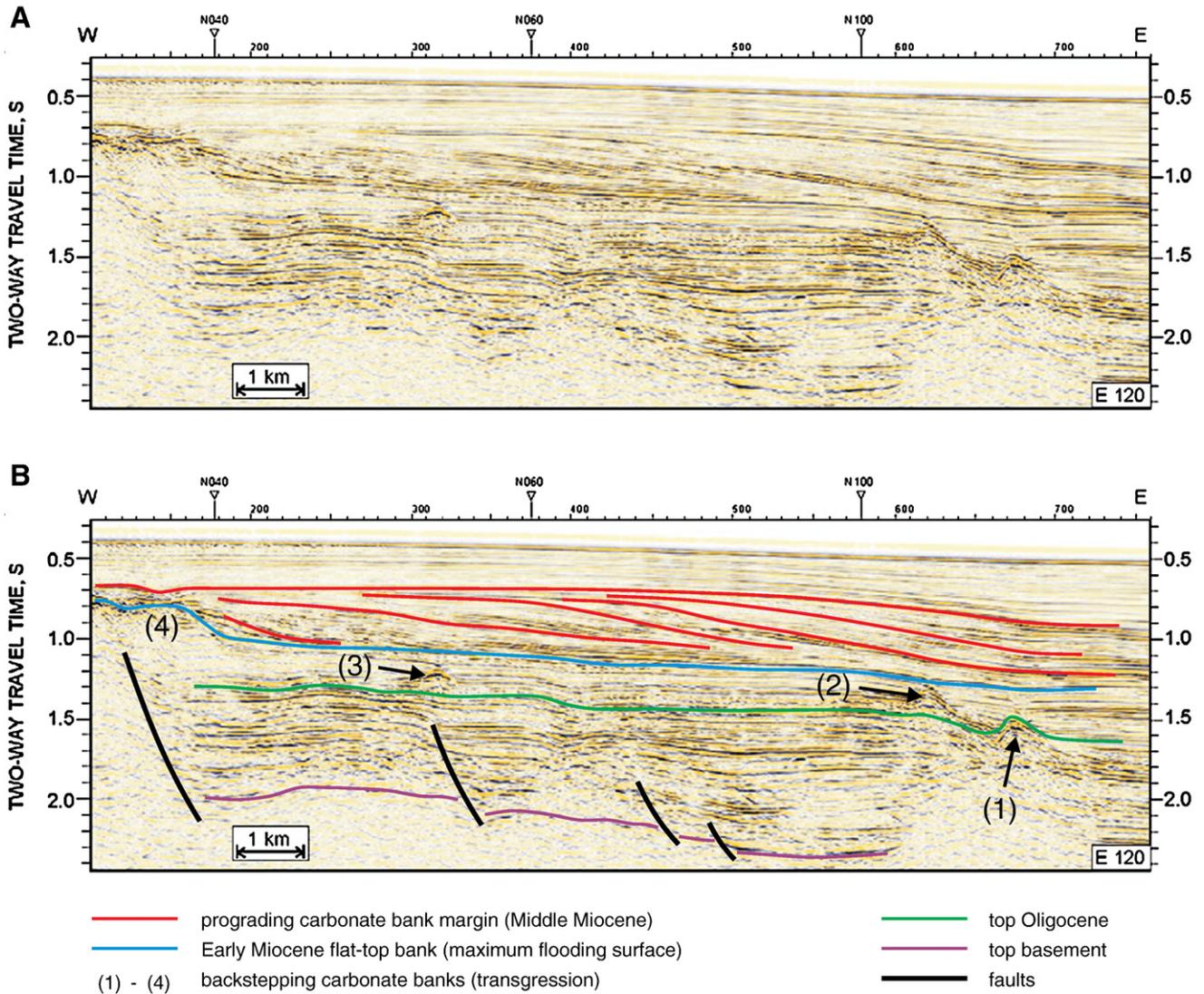


Fig. 21. Uninterpreted (A) and interpreted (B) seismic line showing updip and downdip shifts of a carbonate bank margin (Oligocene–Miocene, Maldives Islands, Indian Ocean; modified from Belopolsky and Droxler, 2003). Depositional trends change from retrogradation (transgression: late Oligocene to early Miocene) to progradation (highstand normal regression: middle Miocene). On seismic lines, the pattern of backstepping is often easier to observe in carbonates than it is in siliciclastics (compare with Fig. 19). The boundary between the transgressive and highstand systems tracts is represented by the maximum flooding surface (downlap surface).

transgressions. Over shorter periods of time, however, high sediment supply distributary channels within deltaic systems may avulse more frequently, yielding numerous flooding surfaces. Such high-frequency transgressions will only punctuate the parasequence-dominated progradational succession. In this case, a larger scale sequence may exclude a transgressive systems tract, but the higher frequency cycles that are nested within this sequence will include transgressive deposits (i.e., lower rank transgressive systems tracts).

Erosion may obliterate the record of various systems tracts. Tidal and/or wave scouring during transgression may affect the preservation of lowstand normal regressive topsets, and also, potentially, of the underlying forced regressive and highstand normal regressive strata. Fluvial or wind degradation during base-level fall may truncate highstand normal regressive and forced regressive deposits. Sediment starvation during rapid base-level rise may prevent the accumulation or preservation of offshore transgressive facies. There are multiple combinations of what a sequence may preserve in terms of component genetic units (i.e., systems tracts), which is why no single template can provide a solution for every situation. The *common element* between all case studies, however, is the fact that every sequence whose framework is linked to changes in shoreline tra-

jectory consists of one or more of the same genetic types of deposit, namely normal regressive (lowstand and highstand), forced regressive, and transgressive. This is why the core workflow of sequence stratigraphic analysis, irrespective of model, requires the identification of all genetic types of deposit and sequence stratigraphic surfaces that are present in a succession (Fig. 22).

The normal regressive, forced regressive and transgressive genetic types of deposits, and their bounding (sequence stratigraphic) surfaces, are core concepts that are *independent* of the sequence stratigraphic model of choice (Fig. 10). These core concepts are acknowledged by all 'schools', even though they may be assigned different degrees of significance, and are more important than the nomenclature of systems tracts or even the position of sequence boundaries, which are *model-dependent* (Figs. 4 and 10).

4. Model-dependent aspects of sequence stratigraphy

Across the spectrum of existing models (Fig. 23), a sequence stratigraphic surface may be considered a sequence boundary, a systems tract boundary, or even a within-systems tract contact (Figs. 3 and 4). Evidently, no consensus can be reached if one tries to establish which

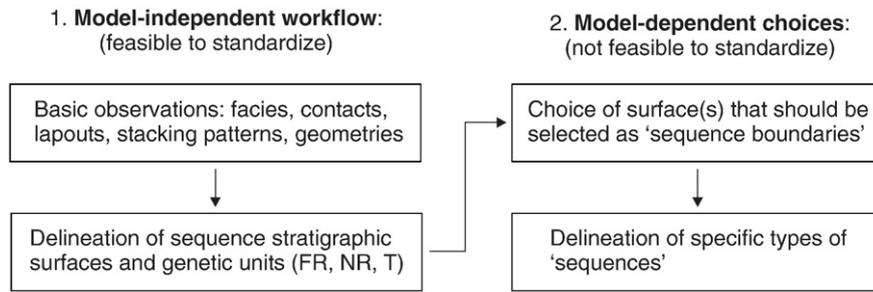


Fig. 22. The method of sequence stratigraphy: standardized workflow versus model-dependent choices. The model-independent workflow leads to the subdivision of the stratigraphic section into a succession of genetic units (systems tracts) separated by sequence stratigraphic surfaces. Once this sequence stratigraphic framework is built, the interpreter may make model-dependent choices with respect to the selection of surfaces that should be elevated to the status of sequence boundary. The nomenclature of sequence stratigraphic surfaces and systems tracts is also model-dependent to some extent (Fig. 10), but a standard set of terms can be recommended to facilitate communication between all practising geoscientists. The nomenclature of systems tracts is particularly difficult to reconcile (Fig. 4), which is why the definition of genetic units with reference to shoreline trajectories (i.e., forced regressive; lowstand and highstand normal regressive; transgressive) offers an unbiased solution to this problem. Abbreviations: FR – forced regressive; NR – normal regressive (lowstand and highstand); T – transgressive.

specific sequence stratigraphic surface(s) should be elevated to the status of sequence boundary. Rigid definition of sequences and sequence boundaries makes no difference to the applicability of the sequence stratigraphic method, which requires the correct identification of *all* sequence stratigraphic surfaces and the genetic character of

deposits in the stratigraphic section under analysis. A generic definition of a 'sequence' that satisfies all approaches, while leaving the selection of sequence boundaries to the discretion of the individual, provides the flexibility that allows one to adapt to the particularities of each case study (Fig. 10).

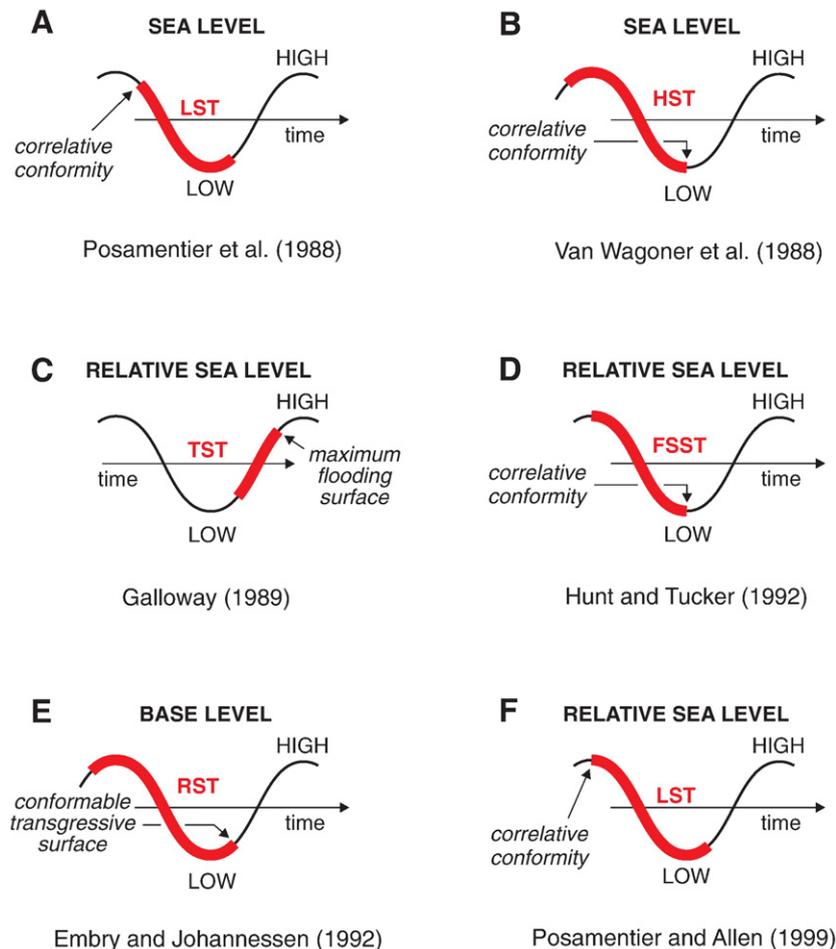


Fig. 23. Correlative conformities as defined by different sequence stratigraphic models (from Catuneanu, 2006). The timing of formation of correlative conformities may be independent of sedimentation (models A, B, D and F), or dependent upon sedimentation (models C and E). Each correlative conformity shown in this diagram corresponds to a particular type of stratigraphic surface shown in Fig. 15: the correlative conformity *sensu* Posamentier et al. (1988) and Posamentier and Allen (1999) (models A and F); the correlative conformity *sensu* Hunt and Tucker (1992) (models B and D); the 'maximum flooding surface' (model C); and the 'maximum regressive surface' (model E). The thicker portion of the reference sine curve in each diagram represents the timing of formation of particular systems tracts considered in those models (see abbreviations). Abbreviations: LST – lowstand systems tract; HST – highstand systems tract; TST – transgressive systems tract; FSST – falling-stage systems tract; RST – regressive systems tract.

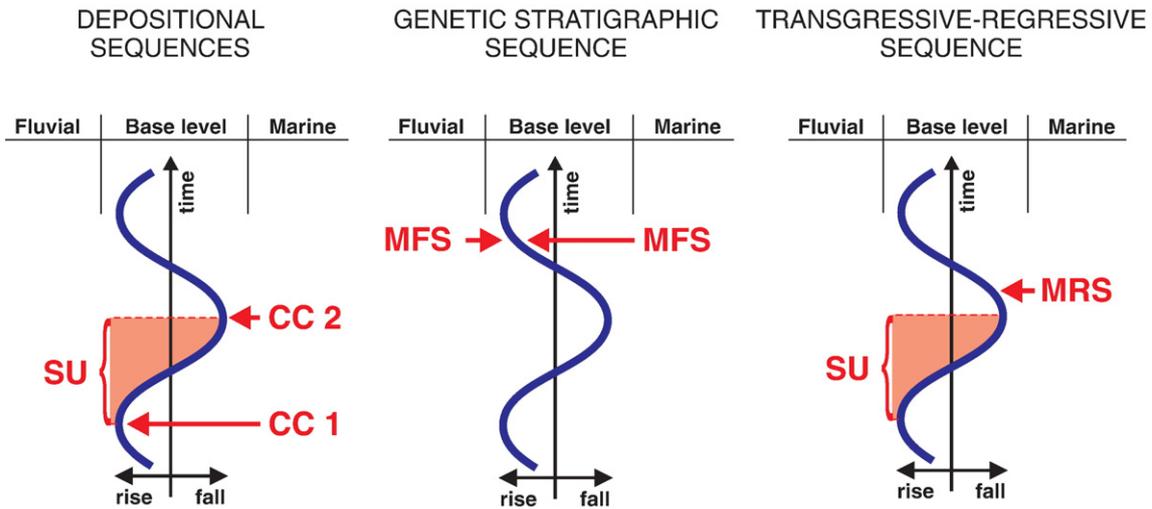


Fig. 24. Selection of sequence boundaries according to the 'depositional', 'genetic stratigraphic' and 'transgressive–regressive' sequence models. The choice of sequence boundary is less important than the correct identification of all sequence stratigraphic surfaces in a succession (Fig. 10). Abbreviations: SU – subaerial unconformity; CC 1 – correlative conformity *sensu* Posamentier and Allen (1999); CC 2 – correlative conformity *sensu* Hunt and Tucker (1992); MFS – maximum flooding surface; MRS – maximum regressive surface. The subaerial unconformity is a stage-significant surface, whereas all other surfaces shown in this diagram are event-significant (Figs. 15, 16).

The large body of sequence stratigraphic work that is already available demonstrates that no single model is applicable to all cases. For example, the subaerial unconformity is largely regarded as the most significant kind of stratigraphic hiatus in the rock record, and hence it is commonly selected as the nonmarine portion of the sequence boundary. While the stratigraphic significance that is attributed to this surface is valid in many case studies, variations in the temporal scale of stages of base-level fall and base-level rise, as well as in the relative duration of forced regressions, normal regressions and transgressions, could generate situations where more time is represented by condensed sections and the unconformable portions of maximum flooding surfaces than in the nearest subaerial unconformities (Galloway, 1998, 2001a, 2002). More importantly, in many situations it may be easier to identify condensed sections than it is to identify subaerial unconformities (Galloway, 1989; Posamentier and Allen, 1999). Such divergent approaches to the selection of the surface that might constitute the sequence boundary, and to the definition of a 'sequence', underline our view that no single model can be generalized so as to provide a framework for the entire range of all possible examples. Instead, stratigraphic patterns have to be analyzed on a case-by-case basis to decide which set of surfaces represented in that particular succession can provide the best boundaries for correlating and mapping 'relatively conformable successions of genetically related strata' (Fig. 10).

The selection of stratigraphic surfaces considered by the 'depositional', 'genetic stratigraphic' and 'transgressive–regressive' sequence models for the nonmarine and marine portions of the sequence boundary is illustrated in Fig. 24. Each sequence stratigraphic model has its own merits and pitfalls.

4.1. Depositional sequences

'Depositional' sequences are bounded by subaerial unconformities and their marine correlative conformities (Fig. 24). Subaerial unconformities remain widely used as sequence boundaries, as they commonly mark significant hiatuses in the stratigraphic record. However, shortcomings related to their use as sequence boundaries include: (1) their potentially cryptic expression when represented by paleosols; (2) they, or portions thereof, may be eroded during subsequent transgression; and (3) the dependency on base-level fall to define sequences. The last point implies that cyclicity developed during stages of base-level rise (e.g., due to fluctuations in the rates of

sedimentation and/or base-level rise) may not be described in terms of depositional sequences. Correlative conformities are taken either at the base (e.g., Haq et al., 1987; Posamentier et al., 1988; Posamentier and Allen, 1999) or at the top (e.g., Van Wagoner et al., 1988, 1990; Christie-Blick, 1991; Hunt and Tucker, 1992; Plint and Nummedal, 2000) of forced regressive deposits (Figs. 4, 23 and 24). In both approaches, *correlative conformities form independently of rates of sediment accumulation*, corresponding to events that mark the onset or the end of base-level fall at the shoreline (Figs. 15 and 24). Both these events are the same age as, or *correlate in time* (hence, 'correlative conformities') with the stratigraphic hiatus associated with the subaerial unconformity (Fig. 24). Depositional sequences are not bounded by maximum regressive or maximum flooding surfaces, the timings of which are offset relative to the timing of subaerial unconformities (Fig. 24). Along strike, the correlative conformities are closer to time lines than surfaces that mark the end of shoreline regression or transgression (Fig. 15). Correlative conformities may be difficult to detect in shallow-water systems, where seismic data are not available, but are much easier to map in deep-water systems (Posamentier and Kolla, 2003; Catuneanu, 2006). Regardless of systems-tract terminology and the choice of correlative conformities, all depositional sequence models acknowledge the importance of separating forced regressive, normal regressive (lowstand and highstand) and transgressive deposits as distinct genetic units. This distinction is more evident in the case of the depositional sequence IV model (Fig. 4), where forced regressive deposits are assigned to a distinct systems tract.

4.2. Genetic stratigraphic sequences

The 'genetic stratigraphic' sequence model (Galloway, 1989) uses maximum flooding surfaces as sequence boundaries (Figs. 4, 23 and 24). This approach has the advantage that maximum flooding surfaces are typically among the easiest sequence stratigraphic surfaces to distinguish in all marine depositional systems, and with virtually any type of data set. Criteria for mapping maximum flooding surfaces in the downstream-controlled portion of fluvial systems are also available (e.g., Shanley and McCabe, 1991, 1993; Shanley et al., 1992; Shanley and McCabe, 1994; Hamilton and Tadros, 1994). Another advantage with this approach is that the definition of genetic stratigraphic sequences is independent of subaerial unconformities, and, implicitly, of base-level fall. This means that the model can be

applied to all types of cycles, including those that develop during continuous base-level rise. However, where subaerial unconformities are present, they are included within the individual sequence. This could, in some cases, lead to the placement of genetically unrelated strata (from below and above the subaerial unconformity) within the same 'sequence'. In contrast to correlative conformities bounding sequences in the 'depositional sequence' model, the timing of formation of maximum flooding surfaces depends on sedimentation, and hence they may be more diachronous, especially along strike (Martinsen and Helland-Hansen, 1995; Posamentier and Allen, 1999; Catuneanu, 2006). As in the case of the depositional sequence models, the genetic stratigraphic approach recognizes the importance of separating forced regressive, normal regressive (lowstand and highstand) and transgressive deposits as distinct genetic units.

4.3. Transgressive–regressive sequences

A 'transgressive–regressive' (T–R) sequence has been defined originally as a sedimentary unit deposited during the time between the beginning of one transgressive event and the beginning of the next, providing that the two transgressive events are of similar scale (Johnson and Murphy, 1984; Johnson et al., 1985). This type of sequence was particularly applicable to marine settings, where evidence of transgressions and regressions could be documented. Subsequent reiteration of the T–R sequence model has combined the marine sequence boundary of Johnson and Murphy (1984) with the fluvial sequence boundary of the depositional sequence model. In this revised definition, the T–R sequence model uses a composite sequence boundary which includes the subaerial unconformity and the marine portion of the maximum regressive surface (Embry and Johannessen, 1992; Figs. 4, 23 and 24). This model emphasizes the importance of subaerial unconformities, as originally outlined by the depositional sequence school (e.g., Haq et al., 1987; Posamentier et al., 1988; Van Wagoner et al., 1988, 1990; Christie-Blick, 1991), and the ease of recognition of maximum regressive surfaces in shallow-water systems. However, a number of limitations include: (1) maximum regressive surfaces may be cryptic in deep-water systems, where they may occur within an undifferentiated succession of leveed-channel low-density turbidites (Posamentier and Kolla, 2003; Posamentier and Walker, 2006; Catuneanu, 2006); (2) the formation of maximum regressive surfaces depends on sedimentation, and hence they may be highly diachronous along strike; (3) the fluvial and marine segments of the sequence boundary are of different ages (Figs. 15, 16 and 24), and so they may only connect physically where the intervening lowstand normal regressive deposits are missing (e.g., a situation when transgression follows shortly the onset of base-level rise as has occurred in the major glacio-eustatic cycles of the late Quaternary); and (4) all 'normal' and 'forced' regressive deposits are included within one 'regressive systems tract', which may be con-

sidered an over-generalization because each of these genetic types of deposits offers different petroleum play opportunities.

5. Recommendations

This section seeks to define a standard workflow and a common language to work with, listing definitions and terminology for the common genetic units and bounding surfaces associated with sequence stratigraphy. We recommend the use of this nomenclature, which recognizes the precedence that comes from publication, the fact that the science has evolved and definitions need to be updated, and the need for a streamlined methodology that is devoid of model-dependent ambiguities.

5.1. Standard workflow

The section on 'Allostratigraphic Units' in the 2005 North American Stratigraphic Code (NACSN, 2005; articles 58, 59 and 60) can serve as an example of how standardization of sequence stratigraphy may be approached and accomplished. Sequence stratigraphy needs to be presented as a *method*, with a standardized workflow that is independent of any model of choice (Fig. 22). The model-independent workflow assumes the subdivision of the stratigraphic section into a succession of genetic units (forced regressive, lowstand and highstand normal regressive, transgressive; i.e., systems tracts) separated by sequence stratigraphic surfaces. Once this generic sequence stratigraphic framework is constructed, the interpreter may make model-dependent choices with respect to the selection of which are the surfaces that should be elevated to the status of 'sequence boundary' (Fig. 22). Such choices may be influenced by personal preferences (approach), available data sets, tectonic and depositional setting, and scale of observation.

In analyses that involve both nonmarine and marine systems, it is required that the two segments of the 'sequence boundary' be age-equivalent at the coastline, so that they always form a single, through-going physical surface from the fluvial to the marine portion of the basin. Two types of sequence comply with this requirement without exception and at any scale of observation: (1) depositional sequences, bounded by subaerial unconformities and their marine correlative conformities; and (2) genetic stratigraphic sequences, bounded by maximum flooding surfaces and their nonmarine correlative surfaces. The former are consistent with the historical usage of Sloss (1963), although at potentially different scales. The latter may provide a more pragmatic approach in light of ease of interpretation of maximum flooding surfaces relative to subaerial unconformities, especially in sections dominated by marine strata. Transgressive–regressive sequences may also provide the means to correlate between nonmarine and marine systems, where lowstand normal regressions are very brief and/or their topsets are missing from the rock record. These conditions are easier to meet in the

Sequence stratigraphy (Posamentier et al., 1988; Van Wagoner, 1995): the study of rock relationships within a time-stratigraphic framework of repetitive, genetically related strata bounded by surfaces of erosion or nondeposition, or their correlative conformities.

Sequence stratigraphy (Galloway, 1989): the analysis of repetitive genetically related depositional units bounded in part by surfaces of nondeposition or erosion.

Sequence stratigraphy (Posamentier and Allen, 1999): the analysis of cyclic sedimentation patterns that are present in stratigraphic successions, as they develop in response to variations in sediment supply and space available for sediment to accumulate.

Sequence stratigraphy (Catuneanu, 2006): the analysis of the sedimentary response to changes in base level, and the depositional trends that emerge from the interplay of accommodation (space available for sediments to fill) and sedimentation.

Fig. 25. Definitions of sequence stratigraphy. In the simplest sense, sequence stratigraphy studies stratal stacking patterns and changes thereof in a temporal framework.

case of short-term (smaller scale) cycles, but the model is increasingly difficult to apply at larger scales of observation (Figs. 7 and 19).

The need for type sections in sequence stratigraphy is less stringent than in the case of other stratigraphic disciplines, because of the change in stratigraphic character of sequences and systems tracts across their areas of occurrence. Sequences and systems tracts are stratigraphic units that are delineated in outcrop or subsurface on the basis of stratal stacking patterns and identification of key bounding surfaces, at various scales of observation. Such units may record different durations, thicknesses and facies along dip and strike. This makes it difficult to select a single type section as a “standard with which spatially separated parts of the unit may be compared” (Neuendorf et al., 2005). However, type sections can be defined for each sequence stratigraphic unit to establish stratigraphic position relative to adjacent units. Such type sections can be used as reference sections for regional correlation. As is the case with other types of stratigraphic units, type sections can be defined in outcrop or subsurface, as many sequence stratigraphic units are only mapped in the subsurface, without outcrop equivalents.

5.2. Definition of sequence stratigraphy

Several definitions of sequence stratigraphy have been published (Fig. 25). Fundamentally, sequence stratigraphy studies address *stratal stacking patterns and changes thereof in a chronological framework*. All current definitions of sequence stratigraphy lay stress on: (1) cyclicity (i.e., a sequence represents the product in the rock record of a stratigraphic cycle, whether or not such cycles are symmetrical or asymmetrical relative to a time scale and regardless of the precise cause of the cycle); (2) temporal framework (i.e., the mapping of contemporaneous facies or depositional systems); (3) genetically related strata (i.e., no significant hiatuses are recognized within a systems tract relative to a chosen scale of observation); and (4) the interplay of accommodation and sedimentation.

5.3. Definition of a ‘sequence’

The concept of ‘sequence’ was first defined in a stratigraphic context by Sloss et al. (1949), as a large-scale (group or supergroup level) unconformity-bounded unit. The term was re-defined subsequently in a seismic stratigraphic context, as “a relatively conformable succession of genetically related strata bounded by unconformities or their correlative conformities” (Mitchum, 1977). The latter definition allowed for sequences to be mapped beyond the termination of sequence-bounding unconformities, and at scales smaller than those originally envisaged by Sloss et al. (1949). Subsequent diversification of sequence stratigraphic approaches led to the definition of several types of sequence, including ‘depositional’, ‘genetic stratigraphic’ and ‘transgressive-regressive’ (Figs. 3 and 4). Each of these types of sequence is defined by specific unconformable and conformable portions of the sequence boundary. (Fig. 24). The common element between these models is the fact that a sequence represents the product of sedimentation during a full stratigraphic cycle, irrespective of whether all parts of the cycle are formed or preserved. The fundamental difference is with respect to the ‘event’ that is selected to mark the start and the end of the full cycle (Figs. 15 and 24). In the broadest sense, a ‘stratigraphic sequence’ can be defined as a generic concept that fits the definition of any type of sequence and affords the application of any model of choice:

Stratigraphic sequence: a succession of strata deposited during a full cycle of change in accommodation or sediment supply.

Stratigraphic-sequence boundaries may include both unconformable and conformable portions. The relative development of the unconformable and conformable portions of a bounding surface may depend on the scale of the sequence, depositional setting, and the mechanism(s) driving stratigraphic cyclicity. Changes in accommoda-

tion may be driven by base-level fluctuations or by shifts in the graded fluvial profile in inland settings. Fluctuations in sediment supply, or in the rates of creation of accommodation, may also generate stratigraphic cyclicity during periods of time of positive accommodation.

The definition of a stratigraphic sequence is independent of temporal and spatial scales. The relative importance of stratigraphic sequences is resolved via the concept of hierarchy. Lower rank sequences are commonly nested within higher rank systems tracts. The specification that a sequence corresponds to a full stratigraphic cycle is required to separate a sequence from component systems tracts or parasequences. In order to define a stratigraphic sequence, bounding surfaces have to be represented consistently by the same type(s) of sequence stratigraphic surfaces.

Strata that comprise a stratigraphic sequence of any type may be considered ‘genetically related’ as they belong to the same stratigraphic cycle of sedimentation. However, such a succession of strata may or may not be ‘relatively conformable’, depending on the development and placement of unconformities (e.g., the subaerial unconformity, or the unconformable portion of the maximum flooding surface) relative to the sequence boundaries. Whether unconformities are placed at the sequence boundary (and hence the sequence is ‘relatively conformable’ at the selected scale of observation) or within the sequence, the component systems tracts can be described as ‘relatively conformable’.

5.4. Parasequences

Parasequence: a relatively conformable succession of genetically related beds or bedsets bounded by flooding surfaces (modified after Van Wagoner et al., 1988, 1990).

Flooding surface: a surface across which there is an abrupt shift of facies that may indicate an increase in water depth or a decrease in sediment supply (modified after Van Wagoner et al., 1988, 1990).

Even though the nature of the deposit changes abruptly across a flooding surface, the water depth need not have risen suddenly. Sediment starvation seaward of a transgressing shoreline, or at the top of abandoned prograding lobes, may also lead to condensed sections that give the appearance of abrupt increases in water depth.

Parasequences are commonly used to describe individual prograding sediment bodies in coastal to shallow-water systems. Confusion regarding the meaning of parasequences has arisen with the application of the term to fully fluvial as well as deep-water systems, where the concept of ‘flooding surface’ becomes meaningless. The relevance of this term to these settings has been questioned by Posamentier and Allen (1999). The mappability of parasequences only within coastal and shallow-water systems marks a difference between the concepts of sequence (which may include the entire array of depositional systems across a sedimentary basin) and parasequence (which is geographically restricted to the coastal and shallow-water portion of a sedimentary basin).

The formation of parasequences may be controlled by autocyclic factors, such as lobe switching and abandonment within deltaic systems, or by allocyclic mechanisms. In the latter case, parasequences may be the product of base-level cycles in the Milankovitch frequency band, and so they may be regarded as smaller scale sequences within their area of development (Krapez, 1996; Strasser et al., 1999). It has also been proposed that the term ‘parasequence’ be expanded to include all regionally significant meter-scale cycles, whether or not they are bounded by flooding surfaces (Spence and Tucker, 2007).

5.5. Genetic types of deposit: systems tracts

A sequence may be subdivided into component *systems tracts*, which consist of packages of strata that correspond to specific genetic types of deposit (i.e., forced regressive, lowstand or highstand normal regressive, transgressive; Fig. 2). The original definition by Brown and

Fisher (1977) is generic and devoid of nomenclatural ambiguity, and thus has remained acceptable for all 'schools':

Systems tract: a linkage of contemporaneous depositional systems, forming the subdivision of a sequence (Brown and Fisher, 1977).

Systems tracts are interpreted based on stratal stacking patterns, position within the sequence, and types of bounding surfaces (Van Wagoner et al., 1987, 1990; Van Wagoner, 1995). Changes in stratal stacking patterns are driven by corresponding changes in shoreline trajectory (Fig. 2). The following types of shoreline trajectory define 'conventional' systems tracts.

Forced regression: regression of the shoreline driven by base-level fall (Fig. 16; Posamentier et al., 1992). Forced regressive deposits display diagnostic progradational and downstepping stacking patterns (Figs. 2 and 7). The systems tract nomenclature applied to forced regressive deposits includes 'early lowstand', 'late highstand', 'forced-regressive wedge' and 'falling-stage' (Fig. 4).

Normal regression: regression of the shoreline driven by sediment supply, during a time of base-level rise at the shoreline or at a time of base-level stillstand (Fig. 16). Normal regressions occur where sedimentation rates outpace the rates of new accommodation added due to base-level rise at the shoreline. In a complete scenario, two normal regressions may be expected during a full cycle of base-level change: a lowstand normal regression that follows the onset of base-level rise after a period of base-level fall, and a highstand normal regression during the late stage of base-level rise (Figs. 16, 18 and 19). Normal regressive deposits display a combination of progradational and aggradational depositional trends (Figs. 2, 7 and 18). The systems tract nomenclature applied to lowstand normal regressive deposits includes 'late lowstand' and 'lowstand'. Highstand normal regressive deposits are designated as 'highstand' or 'early highstand' systems tracts (Fig. 4).

Transgression: landward shift of marine or lacustrine systems, triggered by a rise in base-level at rates higher than the sedimentation rates at the shoreline (Fig. 16). Transgressive deposits display diagnostic retrogradational stacking patterns (Figs. 2, 7, 20 and 21). The transgressive deposits belong to the transgressive systems tract (Fig. 4).

Not all systems tracts need be present in each sequence, either because the shape of the base-level curve did not allow one or more systems tracts to form, or because subsequent erosion. Similarly, not all sequences need be divided into 'conventional' systems tracts as defined above. If unconformity-bounded units bear no relation to base-level changes or to changes in shoreline trajectory, then 'conventional' systems tracts that correspond to stages in the base-level cycle at the shoreline become irrelevant as a basis for the subdivision of sequences. In such cases, 'unconventional' systems tracts may be defined instead based on changes in the ratio between depositional elements that can be recognized and correlated regionally (e.g., low-versus high-accommodation systems tracts in upstream-controlled fluvial systems; see 'Discussion' section below).

5.6. Sequence stratigraphic surfaces

Sequence stratigraphic surfaces are surfaces that can serve, at least in part, as boundaries between different genetic types of deposit (i.e., forced regressive, lowstand and highstand normal regressive, transgressive). Four sequence stratigraphic surfaces correspond to 'events' of the base-level cycle, and three others form during stages between such events (Fig. 15). Their assigned degree of importance, from sequence boundary to systems tract boundary or even within-systems tract facies contacts, varies with the model (Fig. 4). The following is a brief definition of the seven surfaces of sequence stratigraphy.

Subaerial unconformity (Sloss et al., 1949): an unconformity that forms under subaerial conditions, as a result of fluvial erosion or bypass, pedogenesis, wind degradation, or dissolution and karstification. Alternative terms include: lowstand unconformity (Schlager, 1992); regressive surface of fluvial erosion (Plint and Nummedal, 2000); and fluvial entrenchment/incision surface (Galloway, 2004).

Subaerial unconformities may form through all or part of the base-level fall (erosion driven by 'downstream controls', as accounted for by conventional sequence stratigraphic models; Fig. 15); during periods of transgression accompanied by coastal erosion (e.g., Leckie, 1994); during periods of climate-driven increase in fluvial discharge; or during tectonically driven isostatic rebound and increased topographic gradients (erosion driven by 'upstream controls'; e.g., Blum, 1994; Catuneanu and Elango, 2001). Subaerial unconformities accounted for by conventional sequence stratigraphic models may continue to form after the end of base-level fall in areas that are beyond the extent of the lowstand and transgressive fluvial deposits (i.e., landward relative to the point of fluvial onlap).

Correlative conformity (*sensu* Posamentier et al., 1988; Posamentier and Allen, 1999): a stratigraphic surface that marks the change in stratal stacking patterns from highstand normal regression to forced regression. It is the oldest marine clinof orm associated with offlap (i.e., the paleoseafloor at the onset of base-level fall at the shoreline; Figs. 2 and 7). In the deep-water setting, this correlative conformity is commonly placed at the base of the basin-floor submarine fan complex. Where offlap is not preserved, this surface marks the change from an increase (upstepping) to a decrease (downstepping) in the elevation of coastal facies. Due to the change in fluvial accommodation from positive to negative at the onset of forced regression, this type of correlative conformity may be marked by an increase in average grain size during continued progradation. Alternative terms include the "basal surface of forced regression" (Hunt and Tucker, 1992).

Correlative conformity (*sensu* Hunt and Tucker, 1992): a stratigraphic surface that marks the change in stratal stacking patterns from forced regression to lowstand normal regression. It is the youngest marine clinof orm associated with offlap (i.e., the paleoseafloor at the end of base-level fall at the shoreline; Figs. 2 and 7). In the deep-water setting, this correlative conformity is commonly placed at the top of the coarsest sediment within the submarine fan complex. Where offlap is not preserved, this surface marks the change from a decrease (downstepping) to an increase (upstepping) in the elevation of coastal facies. Due to the change in fluvial accommodation from negative to positive at the end of forced regression, this type of correlative conformity may be marked by a decrease in average grain size during continued progradation. There are no alternative terms in use.

Regressive surface of marine erosion (Plint, 1988): a subaqueous erosional surface that forms by means of wave scouring in regressive,

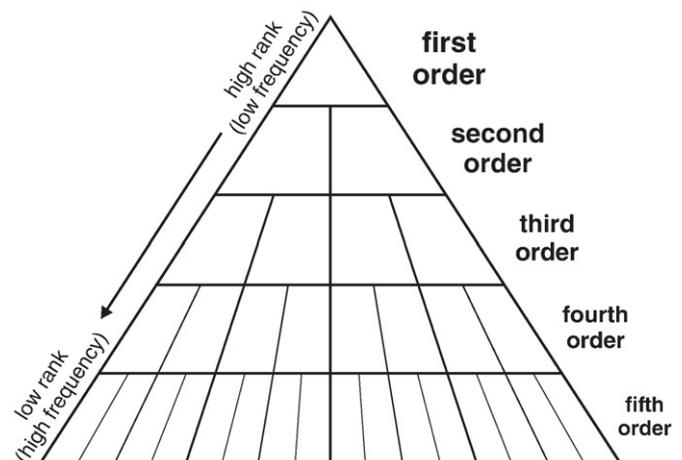


Fig. 26. Diagrammatic representation of the concept of hierarchy. The use of hierarchical orders ('low' versus 'high') in the literature is inconsistent: some refer to first-order cycles as 'high order', making reference to the high position within the hierarchy pyramid, whereas others refer to first-order cycles as 'low order', making reference to the numbering system (1 is lower than 2, etc.). For this reason, we use the less ambiguous terms of 'high rank' versus 'low rank'. These terms make reference to the position of the cycle within the hierarchy pyramid.

wave-dominated lower shoreface to inner shelf settings. This surface is diachronous, younging in a basinward direction. The regressive surface of marine erosion is commonly associated with forced regression, although it may also form under conditions of high-energy normal regression, particularly where the shoreline trajectory is horizontal or rising at a low angle (Helland-Hansen and Martinsen, 1996). Alternative terms include: regressive ravinement surface (Galloway, 2001b); regressive wave ravinement (Galloway, 2004).

Maximum regressive surface (Helland-Hansen and Martinsen, 1996): a surface that marks a change in shoreline trajectory from lowstand normal regression to transgression. It consists of the youngest marine clinof orm, overlapped by transgressive strata, and its correlative surfaces in nonmarine and deep-water settings. Alternative terms include: transgressive surface (Posamentier and Vail, 1988); top of lowstand surface (Vail et al., 1991); initial transgressive surface (Nummedal et al., 1993); conformable transgressive surface (Embry, 1995); surface of maximum regression (Helland-Hansen and Gjelberg, 1994; Mellere and Steel, 1995); maximum progradation surface (Emery and Myers, 1996).

The maximum regressive surface forms during base-level rise, when depositional trends change from coastal progradation to retrogradation. Along each depositional-dip line, this surface corresponds to the end-of-regression event. Along strike, the maximum regressive surface may be highly diachronous, depending on the variations in sediment supply and subsidence rates.

Maximum flooding surface (Frazier, 1974; Posamentier et al., 1988; Van Wagoner et al., 1988; Galloway, 1989): a surface that marks a change in shoreline trajectory from transgression to highstand normal regression. It is commonly a 'downlap surface' in shallow-water settings, where highstand coastlines prograde on top of transgressive condensed sections. Alternative terms include: final transgressive surface (Nummedal et al., 1993); surface of maximum transgression (Helland-Hansen and Gjelberg, 1994); maximum transgressive surface (Helland-Hansen and Martinsen, 1996).

The maximum flooding surface forms during base-level rise, when depositional trends change from coastal retrogradation to progradation. Along each depositional-dip line, this surface corresponds to the end-of-transgression event. Along strike, the maximum flooding surface may record a higher degree of diachroneity, depending on the variations in sediment supply and subsidence rates.

Transgressive ravinement surfaces (Nummedal and Swift, 1987; Galloway, 2001b): erosional surfaces that form by means of wave or tidal scouring during transgression in coastal to upper shoreface settings. Alternative terms include the "transgressive surface of erosion" (Posamentier and Vail, 1988). These surfaces are commonly also flooding surfaces.

Two types of transgressive ravinement surfaces may be recognized, depending on the dominant scouring mechanism: wave-ravinement surfaces (Swift, 1975) and tidal-ravinement surfaces (Allen and Posamentier, 1993). Both types of transgressive ravinement surfaces are diachronous, younging toward the basin margin (Nummedal and Swift, 1987). Their basinward termination joins with the maximum regressive surface; their landward termination joins with the maximum flooding surface.

The criteria that can be used to identify each sequence stratigraphic surface include: the conformable versus unconformable nature of the contact; the depositional systems below and above the contact; the depositional trends below and above the contact; the types of substrate-controlled ichnofacies associated with the contact; and stratal terminations associated with the contact (see Fig. 4.9 in Catuneanu, 2006, for a recent review of criteria).

5.7. Concept of hierarchy

The concept of hierarchy refers to the definition of different orders of cyclicity on the basis of their relative stratigraphic significance (Fig. 26). Hierarchical orders reflect cyclic changes in depositional

trends at different scales of observation. The highest frequency (lowest rank) cycles in the rock record reflect the true changes in depositional trends. All other higher rank cycles represent *trends* that approximate the true facies shifts at increasingly larger scales of observation.

Sequence stratigraphic frameworks can be built at different scales (i.e., hierarchical levels), depending on scope and purpose of the study (e.g., petroleum exploration versus reservoir characterization) or the type of data set available (e.g., seismic versus well logs or outcrop). In the course of subsurface petroleum exploration, it is common that larger scale frameworks are established first, generally based on lower resolution seismic data, followed by the subsequent addition of smaller scale 'details' as more data, such as well logs and cores, become available. As the sequence stratigraphic framework is refined, one can identify higher frequency cycles (e.g., based on well logs) within single seismic reflections. Therefore, the significance of seismic reflections changes with the scale of observation. A seismic clinof orm may represent a single sequence stratigraphic surface, such as a maximum regressive surface or a correlative conformity, within a large-scale stratigraphic framework. At smaller (sub-seismic) scales of observation, such high-rank sequence stratigraphic surfaces may actually represent an amalgamation of multiple high-frequency sequences and surfaces.

Lower rank (higher frequency) sequences and surfaces are nested within higher rank (larger scale) systems tracts, and so sequence stratigraphic units and surfaces of different hierarchical orders may overlap. The discrimination between superimposed units and surfaces that develop at different orders of cyclicity is a matter of scale of observation. Lower rank surfaces superimposed on higher rank ones do not change the stratigraphic significance of the latter within the broader framework. For example, a second-order subaerial unconformity that is overlain by the fluvial topset of a second-order lowstand systems tract may be reworked in part by a third-order transgressive ravinement surface. At the second-order scale of observation, however, the third-order transgressive deposits may not be 'visible', so the contact is still interpreted as a subaerial unconformity at the second-order level. A sequence stratigraphic framework constructed at a particular hierarchical level should be consistent in including stratigraphic surfaces of equal rank.

A stratigraphic section may include a variety of erosional surfaces, from local scours (e.g., the result of slumping, current reworking, or storm-wave erosion) to unconformities with different degrees of stratigraphic or regional significance. At every hierarchical level, a stratigraphic unit can be identified as *relatively conformable* (Mitchum et al., 1977) if the erosional surfaces that develop within that unit are insignificant *at that particular scale of observation*. The scale of observation may be selected purposely to match the objective of a study, or it may be imposed by the resolution of available data. In the former scenario, erosional surfaces of lesser stratigraphic significance relative to the selected scale of observation are included within the higher rank systems tracts and stratigraphic sequences. In the latter scenario, minor erosional surfaces may be 'invisible' in the light of the highest resolution dataset that is available. In such cases, sequence stratigraphic frameworks may be refined subsequently with the identification of lower rank cycles as higher resolution data become available.

The differentiation between units and surfaces that develop at different hierarchical levels may be a function of several criteria, including: temporal duration of stratigraphic cycles; magnitude of stratigraphic hiatuses captured within sequence-bounding unconformities; degree of compositional and geochemical change across sequence-bounding unconformities; degree of structural deformation across sequence-bounding unconformities; regional extent of sequence-bounding unconformities; magnitude of fluvial valley incision associated with sequence-bounding unconformities; magnitude of downstepping (offlap) associated with sequence-bounding unconformities; magnitude of facies shifts across sequence stratigraphic surfaces; and degree of change in paleoflow directions across sequence-bounding unconformities (e.g., Vail et al., 1991; Embry, 1995; Zaitlin et al., 2002;

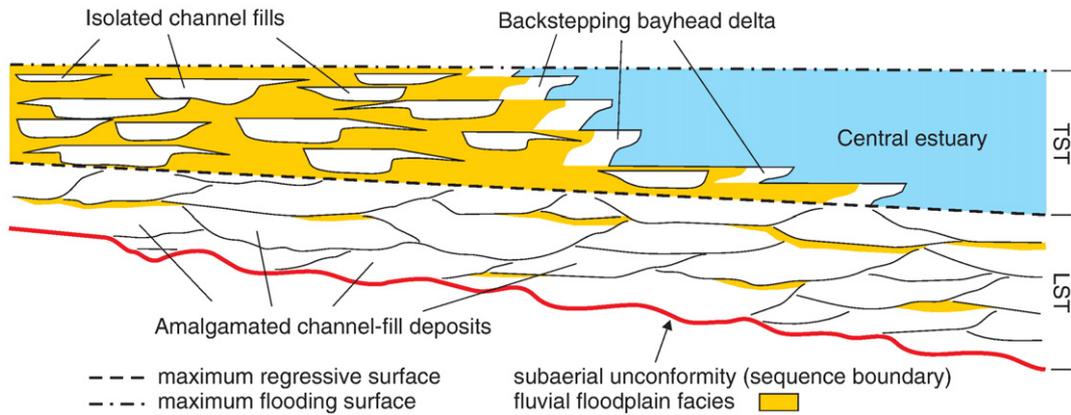


Fig. 27. Dip-oriented stratigraphic cross-section through fluvial to estuarine deposits (modified after Kerr et al., 1999). The lowstand systems tract (LST – lowstand normal regressive deposits) is composed of amalgamated channel-fill facies (low-accommodation conditions) resting on a subaerial unconformity with substantial erosional relief. The transgressive systems tract (TST) consists of floodplain-dominated facies (isolated ribbons encased within floodplain facies, deposited under high-accommodation conditions) and correlative estuarine facies towards the coastline. The maximum regressive surface may be traced at the base of the oldest central estuary facies, and at the contact between amalgamated channel fills and the overlying floodplain-dominated facies farther inland. In this case study, fluvial processes are dominated by ‘downstream controls’ (marine base-level changes). Farther upstream, the maximum regressive surface may eventually onlap the subaerial unconformity.

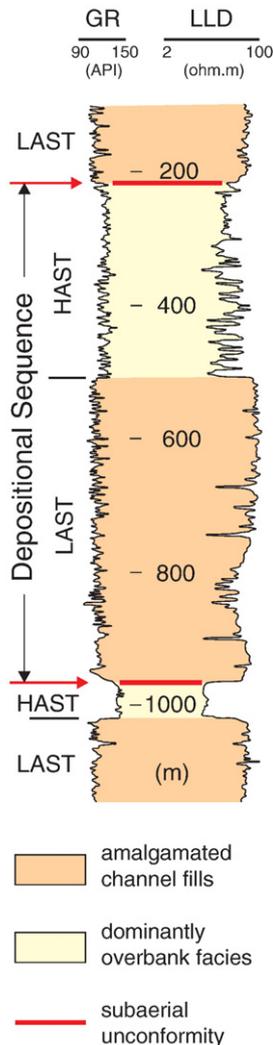


Fig. 28. Fully fluvial succession in an overfilled foreland basin (Miocene, Assam Basin, India; well logs courtesy of the Oil and Natural Gas Corporation, India). The fluvial succession consists of depositional sequences bounded by subaerial unconformities. Abbreviations: LAST – low-accommodation systems tract; HAST – high-accommodation systems tract. The preserved thicknesses of the low- and high-accommodation systems tracts depend on: (1) the spans of time when the conditions for the formation of the two systems tracts were fulfilled; and (2) the amounts of erosion associated with the formation of subaerial unconformities.

Catuneanu, 2006). The applicability and relative importance of these criteria may vary between studies, depending on stratigraphic age (e.g., Phanerozoic versus Precambrian), depositional setting, and the types of data set available (e.g., biostratigraphic, geochronologic, sedimentologic, geochemical, seismic, etc.). The use of different criteria may lead to the development of hierarchical systems that lay emphasis on different attributes of the stratigraphic record, such as time versus physical features that can be mapped in the absence of time control. However, regardless of approach, the generic definition of the concept of hierarchy, which implies that there is a *structured relationship between hierarchical levels*, remains valid and allows for flexible application that suits the particularities of every individual case.

6. Discussion: variability of the sequence stratigraphic model

The most straightforward application of the sequence stratigraphic method is afforded by areas adjacent to the coastline (in particular, coastal to shallow-water settings), where all seven surfaces of sequence stratigraphy may form (Fig. 17). Even in such settings, differences in sediment supply between siliciclastic and carbonate/evaporite systems (extrabasinal versus intrabasinal, respectively) may trigger changes in the development of equivalent systems tracts. Away from coastal to shallow-water settings, the sequence stratigraphic method may become more difficult to apply within nonmarine and deep-water environments, where fewer types of sequence stratigraphic surfaces may form (Fig. 17).

The identification of forced regressive, normal regressive (lowstand and highstand) and transgressive deposits is possible when the genesis and the chronology of the sequence stratigraphic framework can be linked to changes in *shoreline trajectory* (Helland-Hansen and Gjelberg, 1994; Helland-Hansen and Martinsen, 1996). Away from coastal areas, sequence-bounding unconformities may also form independently of shoreline shifts, for example in relation to upstream-controlled fluvial processes (e.g., Shanley et al., 1992; Blum and Törnqvist, 2000; Catuneanu and Elango, 2001; Holbrook et al., 2006) or offshore sub-basin tectonism (e.g., Fiduk et al., 1999). Units bounded by such unconformities are ‘sequences’ in the generic sense of unconformity-bounded units, but their internal architecture cannot be described in terms of conventional systems tracts because they lack the genetic link with coastal processes and trajectories.

6.1. Nonmarine settings

Sequence concepts are applicable, with modifications, to successions that are entirely nonmarine in origin, even where there are no

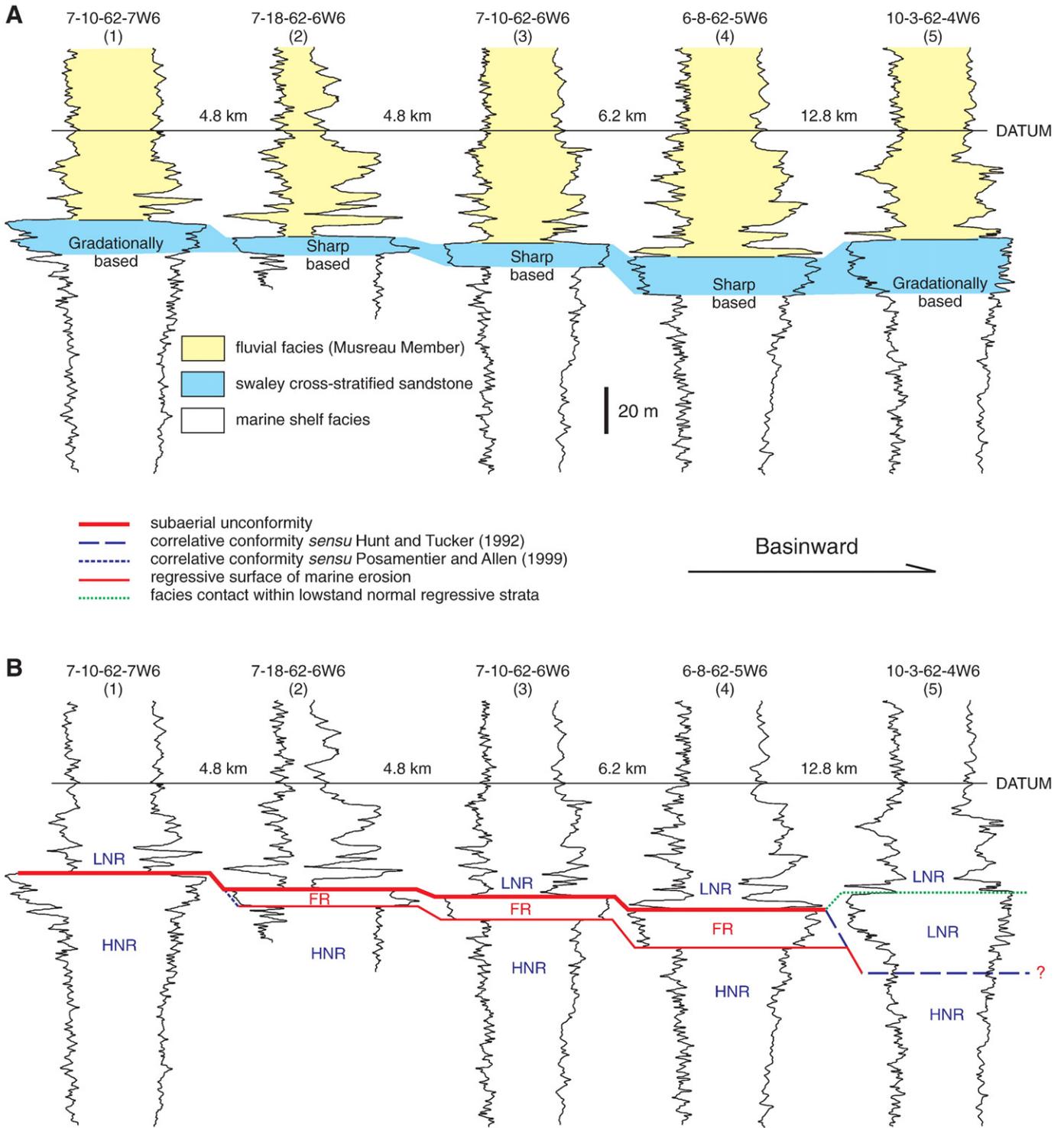


Fig. 29. Sequence stratigraphic interpretation of the swaley cross-stratified sandstone of the Kakwa Member (Cardium Formation), and adjacent units (modified after *Plint, 1988*). A. Sedimentary facies. As constrained by outcrop and core studies, the contact between the fluvial and the underlying shoreface facies is unconformable in wells (1), (2), (3) and (4), and conformable in well (5). B. Sequence stratigraphic interpretation. Correlative conformities are difficult to detect on well logs, within regressive successions of coarsening-upward shallow-marine facies. Correlative conformities are easier to detect on seismic lines, where stacking patterns such as offlap can be observed (e.g., *Fig. 7*). Note the downstepping of the subaerial unconformity during forced regression; the thinning of sharp-based shoreface deposits toward the basin margin; and the aggradation recorded by the lowstand normal regressive strata. In this example, gradationally-based shoreface deposits indicate normal regression (highstand to the left; lowstand to the right), whereas sharp-based shoreface deposits are diagnostic for forced regression. This criterion allows the separation between normal and forced regressive deposits even in the absence of seismic data. Abbreviations: FR – forced regressive; HNR – highstand normal regressive; LNR – lowstand normal regressive.

marine surfaces with which to correlate. In the fully nonmarine environment, fluvial accommodation is created and destroyed by: (1) differential tectonic movement between basin and source area(s), which may modify the amounts of sediment supply and the gradients

of the landscape profile; and/or (2) cycles of climate change that may alter the balance between fluvial discharge and sediment load. These are ‘upstream controls’ on fluvial processes, as opposed to ‘downstream controls’ represented by marine base-level fluctuations

(Shanley and McCabe, 1991; Shanley et al., 1992; Shanley and McCabe, 1993, 1994; Posamentier and Allen, 1999; Blum and Törnqvist, 2000; Catuneanu, 2006; Holbrook et al., 2006).

In inland fluvial settings governed by upstream controls, there is no transgressive ravinement or forced regression, but subaerial unconformities are widespread, and may be used to define sequence boundaries (Gibling et al., 2005). Concepts such as transgression and regression do not apply, unless correlation with a coeval coastline can be established (e.g., Kerr et al., 1999; Fig. 27), but unconventional systems tracts such as 'low-accommodation' versus 'high-accommodation' may be useful for regional correlation (e.g., Olsen et al., 1995; Martinsen et al., 1999; Boyd et al., 2000; Arnott et al., 2002; Zaitlin et al., 2002; Leckie and Boyd, 2003; Ramaekers and Catuneanu, 2004; Leckie et al., 2004; Fig. 28). Such systems tracts are defined by the ratio between fluvial architectural elements. The existence of amalgamated channel deposits is interpreted to indicate a low-accommodation setting, in contrast to floodplain-dominated successions which are interpreted to form under high-accommodation conditions. The change in the degree of channel amalgamation between low- and high-accommodation systems tracts needs not be accompanied by a change in topographic gradient and fluvial style; it may be the mere expression of fluvial sedimentation under varying accommodation conditions.

The formation of subaerial unconformities in upstream-controlled fluvial settings may be attributed to stages of increased fluvial energy, which may be triggered by tectonic or climatic forcing. In such settings, the timing of fluvial erosion and sedimentation may be out of phase with cycles driven by marine base-level changes. For example, deglaciation may trigger fluvial erosion upstream, due to an increase in discharge, while sea-level rise and fluvial aggradation occur downstream. Attempts to recognize 'conventional' systems tracts, which are tied to base-level cycles, are inappropriate unless components of the fluvial succession can be correlated with marine successions downstream (e.g., Kerr et al., 1999; Fig. 27). The responses of fluvial systems to allogenic forcing are complex, and have been reviewed elsewhere (e.g., Summerfield, 1985; Pitman and Golovchenko, 1988; Butcher, 1990; Miall, 1991; Schumm, 1993; Zaitlin et al., 1994; Ethridge et al., 1998; Holbrook and Schumm, 1998; Blum and Törnqvist, 2000; Catuneanu and Elango, 2001; Holbrook, 2001).

6.2. Coastal to shallow-water siliciclastic settings

The application of the sequence stratigraphic method to coastal and shallow-water siliciclastic settings has been widely documented (e.g., Plint, 1988; MacEachern et al., 1992; Allen and Posamentier,

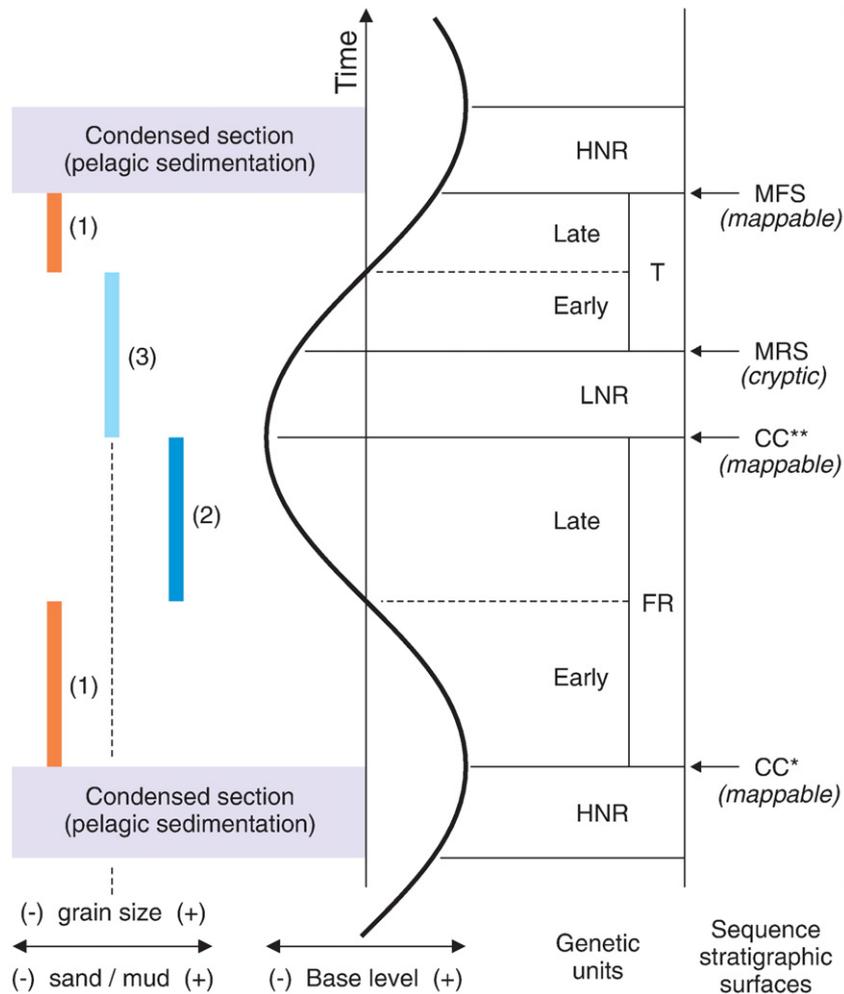


Fig. 30. Dominant types of gravity-flow deposits that form the submarine fan complex in a deep-water setting (modified from Posamentier and Kolla, 2003; Catuneanu, 2006): (1) mudflow deposits, dominated by lobes; (2) high-density turbidites, dominated by frontal splays; (3) low-density turbidites, dominated by leveed channels. The sequence stratigraphic interpretation of the submarine fan complex is more challenging where correlation with the coastal and shallow-water settings cannot be established. However, the predictable change in sediment supply to the deep-water setting during the various stages of the base-level cycle allows for the construction of a sequence stratigraphic framework. See text for more details. Abbreviations: HNR – highstand normal regressive deposits; FR – forced regressive deposits; LNR – lowstand normal regressive deposits; T – transgressive deposits; CC* – correlative conformity *sensu* Posamentier and Allen (1999); CC** – correlative conformity *sensu* Hunt and Tucker (1992); MRS – maximum regressive surface; MFS – maximum flooding surface. See Fig. 31 for a case study.

1993; Bhattacharya, 1993; Hart and Plint, 1993; Ainsworth, 1994; Nummedal and Molenaar, 1995; Pemberton and MacEachern, 1995; Helland-Hansen and Martinsen, 1996; MacEachern et al., 1998; Plint and Nummedal, 2000; Bhattacharya and Willis, 2001; Posamentier, 2002; Hampson and Storms, 2003; MacEachern et al., 2005). Arguably, sequence stratigraphy is easiest to apply in these environments, where the shifts in depositional trends are more evident and all sequence stratigraphic surfaces may form (Fig. 17). Nevertheless, the mappability of these surfaces depends on the type of data that are available for analysis. For example, surfaces for which timing depends on sediment supply (e.g., maximum flooding and maximum regressive surfaces) are easier to detect on well logs than those surfaces the timing of which is independent of sediment supply (e.g., the correlative conformities of the depositional sequence model). Fig. 29 provides an example where the correlative conformities are difficult to pinpoint on any individual log, even though there is evidence to demonstrate the existence of highstand normal regressive, forced regressive and lowstand normal regressive deposits. Where seismic data are available, the observation of stratal (lapout) terminations allows the mapping of correlative conformities (Fig. 7).

The architecture of coastal to shallow-water cycles may vary with the syn-depositional climatic conditions. Depositional sequences formed on continental margins during periods of profound Icehouse climatic and eustatic forcing show a somewhat different stratal architecture from their counterparts formed under Greenhouse climate conditions. Sequences of an Icehouse affinity are typically thin (<50 m, and in many cases <10 m), often organized in stacks of several in

succession, incomplete in terms of systems tracts, and severely top-truncated. Examples of such stratal architecture come from late Paleozoic, Neogene and Pleistocene successions formed under direct or indirect influence of large-scale glacioeustatic sea-level changes. The distinctive vertical stacking pattern initially came to light in studies of Neogene continental margin successions around Antarctica (Bartek et al., 1991, 1997; Fielding et al., 2000, 2001; Naish et al., 2001), but has also been documented from Plio-Pleistocene successions in New Zealand (Naish and Kamp, 1997; Saul et al., 1999), the Miocene Chesapeake Group of eastern USA (Kidwell, 1997), the Miocene of western Chile and Ecuador (Di Celma and Cantalamessa, 2007; Cantalamessa et al., 2005, 2007), and latterly from Lower Permian strata in the Sydney Basin of eastern Australia (Fielding et al., 2006).

A possible explanation for the distinctive motif of sequences of Icehouse affinity is that climate-driven eustasy is more likely to be clearly recorded in an Icehouse world, where the magnitudes of sea-level change and the rates of change are larger and faster, respectively. Examples from the Permian marine record in eastern Australia indicate paleobathymetric changes of 70–80 m for sequences formed during glacial times, whereas similar units deposited in the absence of glacial influence show facies juxtapositions that indicate only 20–30 m shifts across sequence boundaries (Fielding et al., 2008). The temporal scale of such glacial cycles is often within the range of orbital forcing (10^1 – 10^2 kyr; Naish et al., 2001), although a complex interplay of multiple mechanisms that may drive climate changes cannot be ruled out since Icehouse periods have dominated the Earth's climate for millions of years at a time.

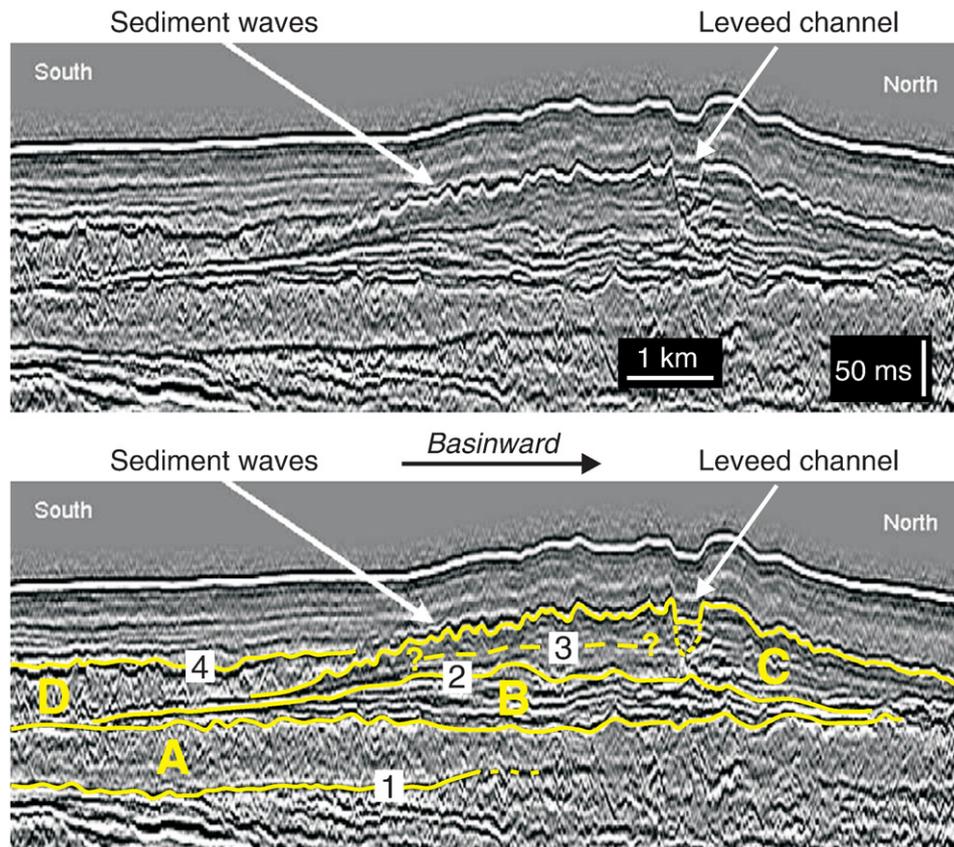


Fig. 31. Uninterpreted and interpreted seismic lines showing a complete basin-floor succession of gravity-flow deposits formed in response to a full cycle of base-level changes (modified from Posamentier and Kolla, 2003). A – mudflow deposits (chaotic internal facies): early stage of forced regression; B – turbidity-flow frontal splay (well-defined parallel reflections): late stage of forced regression; C – leveed channel and overbank facies (high-amplitude reflections associated with the sandy channel fill and weak reflections/transparent facies associated with the finer grained overbank deposits): lowstand normal regressive and early transgressive deposits; D – mudflow deposits (chaotic internal facies): late transgressive deposits. Note the gradual progradation of gravity-flow deposits into the basin from A to C, and the retrogradation from C to D. Sequence stratigraphic surfaces: 1 – correlative conformity *sensu* Posamentier and Allen (1999); 2 – correlative conformity *sensu* Hunt and Tucker (1992); 3 – maximum regressive surface (cryptic, within an undifferentiated succession of low-density leveed-channel turbidites); and 4 – maximum flooding surface.

6.3. Deep-water settings

Three surfaces that are directly correlatable to marine base-level changes and shoreline shifts do not form in the deep-water setting, namely the transgressive ravinement surface, the regressive surface of marine erosion, and the subaerial unconformity. However, a sequence stratigraphic framework may still be constructed by mapping the four event-surfaces which do develop in the deep-water realm (i.e., the two correlative conformities of the depositional sequence model, the maximum flooding surface and the maximum regressive surface; Fig. 17). Besides the lack of development of all seven kinds of surfaces in the sequence stratigraphic paradigm, another factor that challenges the application of the sequence stratigraphic method to deep-water settings is the potential for physical disconnection between the deep-water portion of sequences and their fluvial to shallow-water equivalents. This disconnection is commonly the result of nondeposition or sediment instability and erosion in the shelf edge to upper slope areas. In such cases, the sequence stratigraphic interpretation of the submarine fan complex is more challenging where correlation with the coastal and shallow-water settings cannot be established. However, the predictable change in sediment supply to the deep-water setting during the various stages of the base-level cycle allows for the construction of a sequence stratigraphic framework (Posamentier and Kolla, 2003; Catuneanu, 2006; Posamentier and Walker, 2006).

Recent insights into the types of gravity flows that are expected to form during the different parts of the base-level cycle show that predictable changes in facies and depositional elements may accompany the formation of correlative conformities and maximum flooding surfaces, while maximum regressive surfaces are likely to be cryptic, within undifferentiated successions of aggrading leveed-channel turbidites (Catuneanu, 2006; Posamentier and Walker, 2006; Figs. 30 and 31). The general pattern of deep-water sedimentation shown in Figs. 30 and 31 is controlled by changes in accommodation on the shelf, as well as in the location of the coastline, during various stages of the base-level cycle. These changes control sediment supply (both volume and grain size) to the deep-water setting (see Catuneanu, 2006, for a full discussion). However, both the volume and the grain size of the sediment that is delivered to the deep-water setting may also be modified by the size and the energy of the rivers that bring sediment to the coastline, as well as by the width of the continental shelf. In the case of narrow shelves, sediment supply to the deep-water environment may be higher during all stages of the base-level cycle, but the general trends are maintained in the sense that the lowest volume and the finest sediment will still accumulate during highstand normal regression, whereas the largest volume and the coarsest sediment will still be delivered at the end of forced regression.

In terms of the four 'events' of the base-level cycle (Fig. 15), the onset-of-fall and the end-of-fall are the most significant with respect to changes in sediment supply to the deep-water setting. The former acts as a switch that turns on sediment supply to the deep-water setting, and initiates the formation of the bulk of the submarine fan complex. The latter turns off sediment supply to the deep-water setting, as sediment starts to aggrade on the continental shelf following the onset of base-level rise. The initiation of topset sedimentation on the shelf marks a decrease both in the volume and in the grain size of the sediment that is made available to the deep-water environment (Catuneanu, 2006). Therefore, the significance of a coarsening-upward trend changes between shallow- and deep-water settings. In shallow-water deposits, the top of a coarsening-upward trend may be interpreted as a maximum regressive surface. In the deep-water setting, the coarsest sediment accumulates earlier, during the time of formation of the correlative conformity *sensu* Hunt and Tucker (1992). The onset-of-fall and end-of-fall events correspond to the correlative conformities of the depositional sequence model (Figs. 15 and 24).

The sequence interpretation of deep-water deposits is further complicated by the fact that facies shifts respond only in part to regional

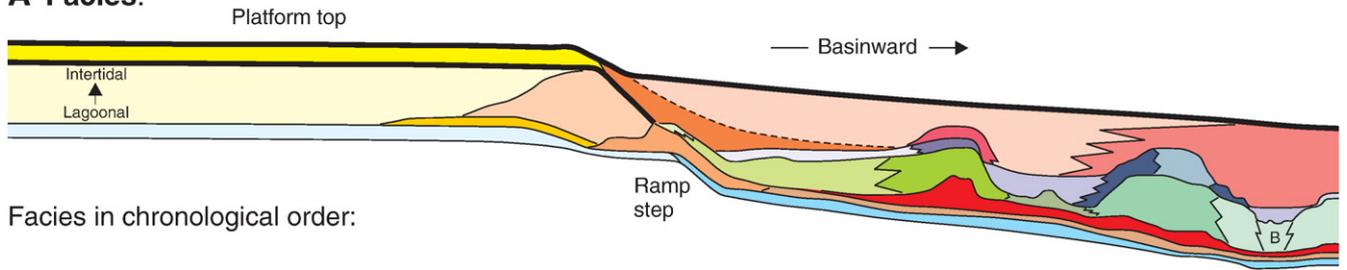
changes in accommodation (e.g., Hiscott et al., 1997). Additional controls may include changes in sediment supply and dispersal patterns, autocyclic processes of fan switching, unpredictable changes in energy flux such as the ones caused by hurricanes, and local accommodation changes caused by underlying salt, shale or basement tectonics that create localized sub-basins (Underhill, 1991; Galloway, 2001b; Sinclair and Tomasso, 2002; Posamentier and Kolla, 2003; Galloway, 2004). While autocyclic and random changes in energy flux may add another level of complexity to the stratigraphic architecture, the depositional elements they generate tend to 'stand out' and may be rationalized within the predictable sequence stratigraphic framework.

6.4. Carbonate settings

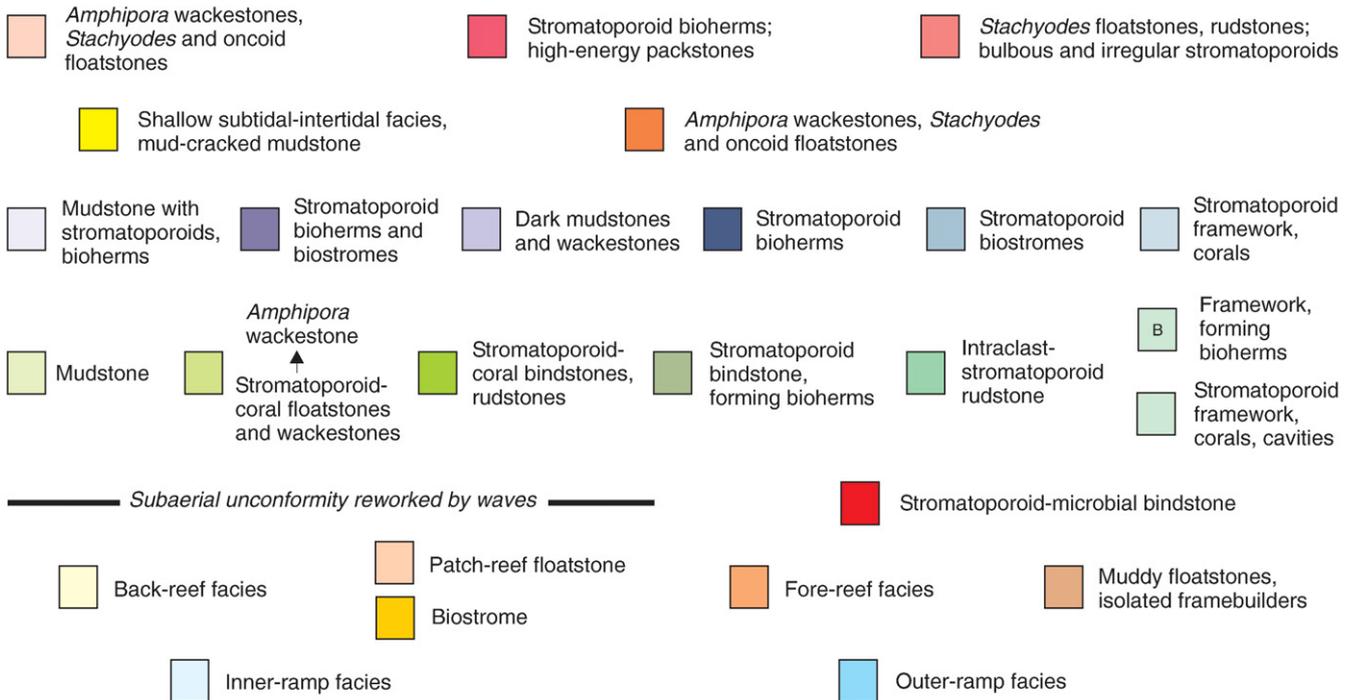
The concepts of sequence stratigraphy apply to carbonate systems in much the same way as they do to siliciclastic or other terrigenous (e.g., detrital calcareous clastic) systems (Sarg, 1988; Handford and Loucks, 1993; Hunt and Tucker, 1993; Cathro et al., 2003; Schlager, 2005). Carbonate stratigraphic sections are thus similarly punctuated by key bounding surfaces that include subaerial unconformities, correlative conformities, maximum flooding surfaces, flooding surfaces, maximum regressive surfaces, regressive surfaces of marine erosion, and transgressive ravinement surfaces (Fig. 32). The difference lies in the physical character of these surfaces and the sediments they subdivide. Most of these differences are tied to the facts that: (1) in carbonate settings sediments are primarily sourced locally in response to the productivity of carbonate-producing organisms, forming the 'carbonate factory'; (2) most carbonate production is related to photosynthesis and so water depth, either directly (in the case of autotrophs, which use inorganic material to synthesize living matter) or indirectly (in the case of heterotrophs, which include filter feeders that are light-independent, and, consequently not controlled by water depth); (3) carbonate production is also related to the salinity, temperature and nutrient content of the seawater; (4) the dispersal of carbonate sediment is influenced by biological processes that include binding, baffling, encrusting, and framework-building; (5) carbonates are prone to cementation penecontemporaneous with accumulation, which stabilizes the sea bottom and thus restricts sediment mobility; and (6) carbonates are prone to physical and chemical erosion in both submarine and subaerial settings. Interpreting key surfaces in a sequence stratigraphic context can be particularly problematical because deposits may be erased and critical events may go unrecorded. It is important to remember that the influence of all these factors is related to the evolutionary and ecological history of the various organism groups involved, be they microbial, faunal or floral.

These collective carbonate responses mean that Jervey's (1988) original definition of accommodation as "the space available for sediment accumulation" is modified for carbonates. The space for carbonate accumulation can be subdivided into 'physical' and 'ecologic' accommodation (Pomar and Kendall, 2007). In keeping with Jervey's (1988) original definition, physical accommodation is the space entirely dominated by the effects of local hydrodynamics that actively link the sea floor to the 'shelf equilibrium profile', as defined by Swift and Thorne (1991). Within this space, loose (uncemented) sediment, be it carbonate or siliciclastic, tends to build up to the shelf equilibrium profile. This surface is the base level that is involved in the creation of the depositional shelf and slope. Eustasy and total sea-floor subsidence, as well as changes in sediment volume, grain size and hydrodynamic (energy) conditions, govern changes in base level, and implicitly in physical accommodation. Loose carbonate sand (oolitic, peloidal, bioclastic) is transported physically by currents and waves which, after building up to the shelf equilibrium profile, may subsequently be shed onto the slope, much as in siliciclastic systems, while carbonate mud is commonly exported from the platform to the slope and basin. Carbonate production in the aphotic zone may add to the volume of sediment exported from the platform.

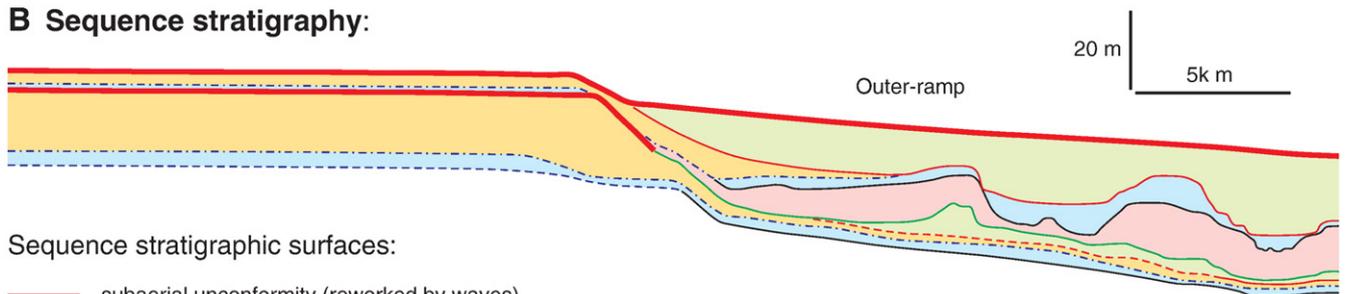
A Facies:



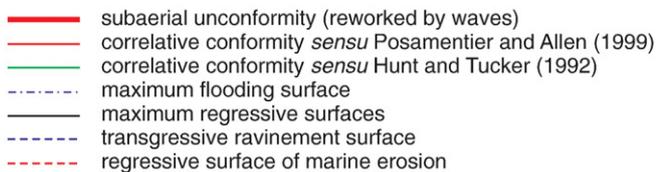
Facies in chronological order:



B Sequence stratigraphy:



Sequence stratigraphic surfaces:



Genetic units (systems tracts):

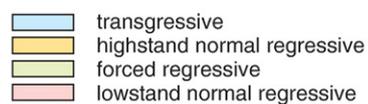


Fig. 32. Architecture of facies, genetic units (systems tracts) and sequence stratigraphic surfaces of a Late Devonian reef system that developed on a gently sloping, epicontinental ramp (Alexandra Formation, Western Canada Sedimentary Basin; modified from MacNeil and Jones, 2006). Vertical exaggeration is 250 times.

By contrast, ecological accommodation is dictated by the capacity of certain organisms to adhere to one another, produce rigid reef frameworks, and hence accumulate above the physical accommodation or hydrodynamic thresholds associated with clastic sedimentation. The spectrum of different carbonate platform types is often a consequence of both types of accommodation operating at the same time but in different areas. Examples of settings influenced by eco-

logical accommodation include: (1) open-shelf platforms involving large-skeleton metazoans and microbial structures like stromatolites with a capacity to build a platform margin above the shelf equilibrium profile but not necessarily to sea level; (2) rigid rimmed platforms with biotic components capable of accumulating to sea level with a maximum ecological accommodation; and (3) platforms with thick marginal slope facies that are composed of sediment generated below

the photic zone as for instance mud-mounds in slope or deep ramp settings. So while the principles of physical accommodation apply to the carbonate depositional settings in general, ecological factors may modify this role.

When base level is rising and new accommodation is being added, whether or not carbonate production increases in tandem will depend on the rate at which new space is added relative to the ability of carbonate productivity to keep up (Fig. 21). Some have argued that a lag time typically occurs before the carbonate-producing organisms reach the optimal ecological conditions needed for them to fill the newly created space (Schlager, 1981; Enos, 1991; Tipper, 1997). Others have considered that there is no lag time involved but that the rise in base level responsible for the increased accommodation is asymmetrical (Denton, 2000). A further consideration related to this is the linear versus non-linear response of carbonate sediment production rate in some systems, tied to the fact that carbonate production may begin or cease when conditions, including temperature or nutrient content, change symmetrically or even linearly (Lukasik and James, 2003; Pomar and Kendall, 2007). In addition, a change in ecological conditions, without significant change of sea level, may induce an increase in accommodation, if it positively affects the carbonate producing biota and its ability to accumulate above the shelf equilibrium profile.

Whatever the cause of reduced carbonate production, when carbonate accumulation cannot keep up with the rate of generation of new accommodation, water depth progressively increases and condensed sections or marine hardgrounds may develop. This decreasing production may not vary linearly with respect to rate of base-level change. Faunal and sedimentological heterogeneity in deposits associated with transgressions can often be of a different character than those of the preceding lowstands or the following highstands. One effect of *in situ* carbonate production in warm shallow water, by comparison to siliciclastic settings, is the potential for the development of thick transgressive systems tracts (Kerans et al., 1995; Kerans and Loucks, 2002). The resulting shape of the platform is a direct response to the productivity of the carbonate factory and different rates of response to base-level change which are imprinted on the underlying structural geometry inherited from the basement or pre-existing strata. This may be related to a response to nutrient supply, driven by climate change, tectonics in the source area, or circulation, which can cause a shift from oligotrophic to meso- and eutrophic conditions (e.g., Homewood, 1996; Lukasik and James, 2003). The maximum flooding surface lies above the transgressive systems tract and is commonly detected at the heart of the condensed section, or at the top of hardgrounds in the case of a starved basin.

Where the rate of carbonate sedimentation manages to keep pace with the rate of accommodation added, either physical or ecological or both, aggradation will take place (Fig. 21). The extent to which progradation occurs depends upon whether carbonate production can overflow the newly created space leading to export and the lateral build out of the margin (Fig. 21). Reefs, tidal flats, and carbonate sand shoals are prone to progradation, whereas other settings are less able to accumulate sediment to sea level. Carbonate platforms limited by steep escarpments have a low potential to prograde by comparison to those with a lower angle profile, although this is also a function of slope height, volume of sediment being shed, and size of the basin. As emphasized by Pomar and Kendall (2007), the style of shedding and outbuilding at the platform margin also depends on whether the carbonate factory is located in the shallow photic zone or below it, as well as the area available for carbonate production, which in turn are a function of the biotic composition of the carbonate factory, basin-floor physiography and position of base level. Progradation tends to yield a downlap surface when the strata thin into the condensed section.

During the early and late stages of base-level rise, carbonates often respond like siliciclastic systems, forming normal-regressive progradational geometries during intervals characterized by relatively slow

rates of accommodation generation (Cathro et al., 2003). In contrast to siliciclastic systems, where accommodation and sedimentation may operate as independent variables, carbonate production during stages of normal regression depends on how the size and the efficiency of the carbonate factory are affected by changes in accommodation. This process–response relationship is often mediated by the seafloor physiography, which controls the areas available for biota to thrive. During lowstand normal regression, the rate of base-level rise increases, resulting predictably in an increased rate of aggradation. During highstand normal regression, the rate of base-level rise decreases, resulting in a decreased rate of aggradation (Fig. 21). In the former case, aggradation will be restricted to just those areas marginal to highstand reefal build-ups. In the latter case, the carbonate factory may experience maximum productivity, leading to a ‘highstand shedding’ of carbonate sediment into the deeper water setting (Droxler and Schlager, 1985; Eberli et al., 1994; Andresen et al., 2003). These depositional trends are common to high-relief, shelf-situated reef systems with steep, narrow margins. By contrast, reef systems that develop on gently sloping epicontinental ramps may not be characterized by high rates of carbonate production or sediment shedding during highstands. Rather, the highest carbonate productivity in the outer ramp area may be recorded during times of base-level fall, resulting in a geometry of systems tracts that resembles the process of ‘lowstand shedding’ that is more typical of siliciclastic systems (MacNeil and Jones, 2006; Fig. 32).

Base-level falls cause negative changes in accommodation. A platform that had been the site of carbonate production during periods of base-level rise may now no longer generate carbonate sediment. Instead, evaporites, karstification and paleosols may develop across the platform top in conjunction with a subaerial unconformity (Fig. 32). Depending on whether the downdip topography is restricted or unconfined, carbonate sediment and/or evaporites may accumulate adjacent to the now exposed carbonate terrains. In areas with a confining topography evaporites may accumulate as sabkha cycles or from local standing bodies of water (e.g., Tucker, 1991; Sarg, 2001). Carbonate producing areas develop at the peripheries of preexisting highstand reefal build-ups, and may be driven basinward as base level falls. In the case of steep-sided platforms, forced regression could result in an almost total shutdown of the carbonate factory. Provided the build-up margins are not too deep or steep for carbonate production, these marginal areas may become the sites of sediment accumulation as a forced regressive deposit (e.g., MacNeil and Jones, 2006; Fig. 32). In addition to new carbonate sediment that may form during base-level fall, a volumetrically significant portion of the forced regressive deposits may be represented by toe-of-slope wedges and/or aprons of limestone megabreccias (Eberli et al., 1994; Spence and Tucker, 1997; Playton and Kerans, 2002). The surface that underlies the forced regressive deposits is the correlative conformity *sensu* Posamentier and Allen (1999), and may be replaced in part by the regressive surface of marine erosion. The surface that overlies the forced regressive deposits is the correlative conformity *sensu* Hunt and Tucker (1992) (Fig. 32). Both correlative conformities are downlapped by overlying regressive deposits, and may merge basinward with the main downlap surface (i.e., the maximum flooding surface) where the underlying highstand systems tract thins into a condensed section.

Strasser et al. (2006) illustrated how carbonate sedimentary cycles record repetitive changes (e.g., in stacking pattern, facies, biological and geochemical composition), often driven by periodic changes in accommodation. These are commonly attributed to changes in the Earth’s orbital parameters that vary with periods of 20 to 100 kyr. The cycles can be correlated and used to estimate effects and rates of paleoclimatic, paleoceanographic, sedimentary, biological, and diagenetic processes, and they may vary in character depending on their position within the nested frequency of base-level change (Spence and Tucker, 2007). Some shallow-water carbonate cycles record evidence

of both base-level rise and base-level fall, consisting of relatively conformable successions of genetically related beds or bedsets that are truncated at the top. Cyclicity may also develop during continued but varying rates of base-level rise (e.g., the ‘punctuated aggradational carbonate cycles’ of Anderson et al., 1984). These units form without development of karstification or significant soil profiles, and generally show no evidence of forced regression.

Carbonate and siliciclastic sediment can either coexist, as mixed systems, or alternate in time and thus conforming to the notion of ‘reciprocal sedimentation’ (Wilson, 1967). The termination of carbonate production and the shift to a siliciclastic system may be attributed to various controls, including: (1) subaerial exposure triggered by base-level fall; (2) rapid base-level rise and consequent drowning of the carbonate system; (3) progradation of siliciclastic systems under normal regressive conditions; and (4) change in climate and ecological conditions. Increase in terrigenous run-off, including both siliciclastic sediment and nutrients, may shift the carbonate system from oligotrophic to meso- and eutrophic until the carbonate factory is eventually shut down. In the case of drowning, the contact between carbonates and the overlying fine-grained hemipelagic facies has been termed the ‘drowning unconformity’ (Schlager, 1989), and has been designated as a special type of sequence boundary in mixed carbonate-siliciclastic successions (Schlager, 1999).

7. Conclusions

Standardization of sequence stratigraphy requires that personal preferences in applying one sequence stratigraphic model over another (Figs. 3 and 4) be kept separate from what is feasible to include in stratigraphic codes or guides. Only the common ground of all approaches can provide an unbiased solution to standardization. This implies a distinction between model-independent and model-dependent aspects of sequence stratigraphy (Fig. 10).

The model-independent platform of the method includes: (1) the fundamental concepts that underlie all current approaches; (2) the definition of different genetic types of deposit on the basis of stratal stacking patterns (i.e., forced regressive, lowstand and highstand normal regressive, and transgressive); (3) the definition of sequence stratigraphic surfaces at the boundary between different genetic types of deposit; and (4) the definition of a model-independent workflow (Fig. 10). The model-independent platform of sequence stratigraphy is feasible to standardize in stratigraphic codes and guides. Outside of this common platform, the interpreter may make model-dependent choices with respect to which sequence stratigraphic surface(s) should be elevated in importance and be selected as sequence boundaries (Figs. 22 and 24). The nomenclature of systems tracts and sequence stratigraphic surfaces is also model-dependent to some extent (Fig. 10), but a standard set of terms is recommended to facilitate communication between all practitioners.

The underlying assumption of all ‘conventional’ sequence stratigraphic approaches is that the genesis and the chronology of the sequence stratigraphic framework are intrinsically linked to changes in shoreline trajectory. In such cases, forced regressive, normal regressive (lowstand and highstand) and transgressive deposits are used to subdivide sequences into conventional systems tracts. Conventional sequence stratigraphy works best for settings that include downstream-controlled fluvial systems, coastal systems, and all marine systems whose sediment supply depends on shoreline shifts. Outside of the area controlled by base-level changes at the shoreline, erosional surfaces produced by upstream-controlled fluvial processes or by offshore processes including sub-basin tectonism may also define ‘sequences’ in the generic sense of unconformity-bounded units. However, these sequences lack a genetic linkage with the coastline, and therefore their internal architecture cannot be described in terms of conventional systems tracts. Such sequences may be subdivided into unconventional systems tracts on the basis of the ratio

between the various depositional elements that may form in those settings.

The optimal approach to the application of sequence stratigraphy relies on the integration of outcrop, core, well-log and seismic data sets. Each provides different insights into the identification of stratal stacking patterns and sequence stratigraphic surfaces, and mutual corroboration is important to reduce the uncertainty of the interpretations. Not all data sets may be available in every case study, a factor which may limit the ‘resolution’ of the sequence stratigraphic interpretation. At the same time, not all types of data are suitable for the detection of all sequence stratigraphic surfaces and systems tracts, and not all sequence stratigraphic surfaces form in every depositional setting (Fig. 17).

The area of transition between fluvial and shallow-water settings affords the formation of the broadest array of sequence stratigraphic surfaces. By contrast, within fluvial and deep-water settings, conditions are favorable for the formation of fewer types of bounding surfaces (Fig. 17). In analyses that involve both nonmarine and marine settings, it is required that the two portions of the ‘sequence boundary’ be age-equivalent at the coastline, so that they always form a single through-going physical surface, at any scale of observation. Two types of sequences comply with this requirement, without exception (Fig. 24): (1) depositional sequences, bounded by subaerial unconformities and their marine correlative conformities; and (2) genetic stratigraphic sequences, bounded by maximum flooding surfaces and their nonmarine correlative surfaces. In the case of transgressive-regressive sequences, the preservation of lowstand topsets may prevent the physical connection between the nonmarine and the marine portions of the sequence boundary. This pitfall is particularly evident in the case of larger scale (higher rank) stratigraphic cycles (Figs. 7 and 19).

The geomorphic, tectonic and dynamic settings have a strong influence on the way in which the changes in accommodation are expressed or preserved. Thus, there are multiple combinations of what a sequence may preserve in terms of component systems tracts, which is why no single template can provide a solution for every situation. The common element between all case studies, however, is the fact that every sequence whose framework is linked to changes in shoreline trajectory consists of one or more of the same genetic types of deposits (i.e., forced regressive, lowstand and highstand normal regressive, transgressive). This is why a standardized workflow of sequence stratigraphic analysis emphasizes the identification of genetic types of deposits and sequence stratigraphic surfaces, which can be used to subdivide the stratigraphic section into component systems tracts (Fig. 22). Beyond this model-independent framework of genetic units and bounding surfaces, the selection of which surface(s) should be elevated to the rank of ‘sequence boundary’ may vary with the approach, depositional setting, data set, and scale of observation.

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